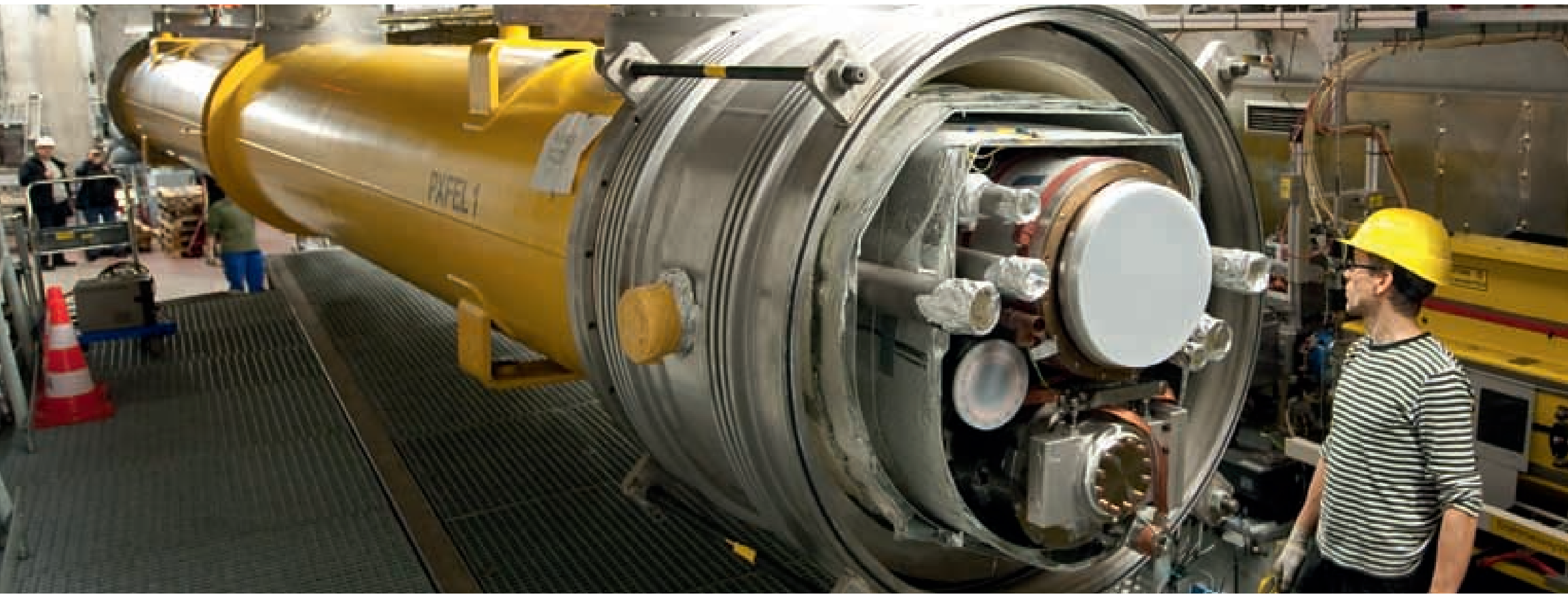
SPEED MACHINES.

DESY develops, constructs and operates accelerators to boost particles up to top speed



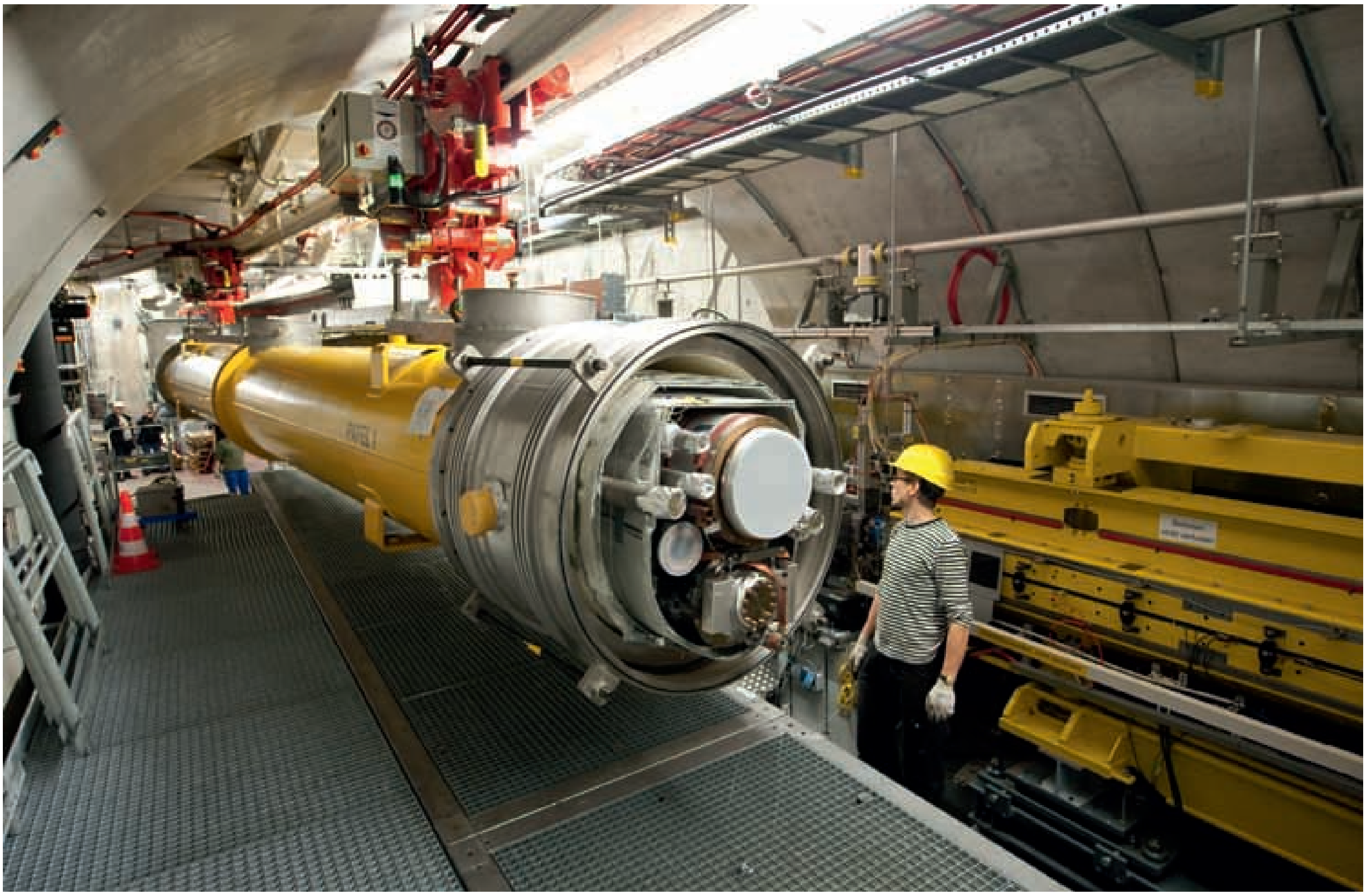
The development of particle accelerators entails special challenges for humans and technology alike. Time and again, it is necessary to break new ground and push back the frontiers of technology. Close cooperation with industry plays an important role in this respect. Over more than 50 years, DESY has accumulated vast experience in the development, construction and operation of particle accelerators. Today it is one of the world's leading authorities in this field.

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

DESY

Installation of an accelerator module in the free-electron laser FLASH at DESY. The module will enable the FLASH facility to boost electrons to an energy of 1.2 gigaelectronvolts and thus generate laser light with wavelengths down to around 4.5 nanometres. The module is a prototype for the X-ray laser European XFEL, which will provide even shorter wavelengths in the hard X-ray range starting in 2014.



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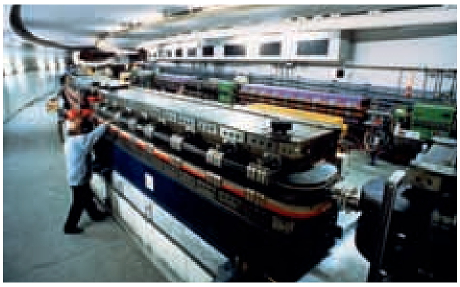


DESY.

Insight starts here

DESY is one of the world's leading accelerator centres for investigating the structure of matter. DESY develops, builds and uses particle accelerators and detectors for photon science and particle physics.

DESY carries out fundamental research in a range of scientific fields and focuses on three principal areas:

- **Accelerators:**
  DESY develops, builds and operates large facilities that accelerate particles to extremely high energies.

- **Photon science:**
  Physicists, chemists, geologists, biologists, medical researchers and material scientists use the special light from DESY's accelerators to study structures and processes in the microcosm.

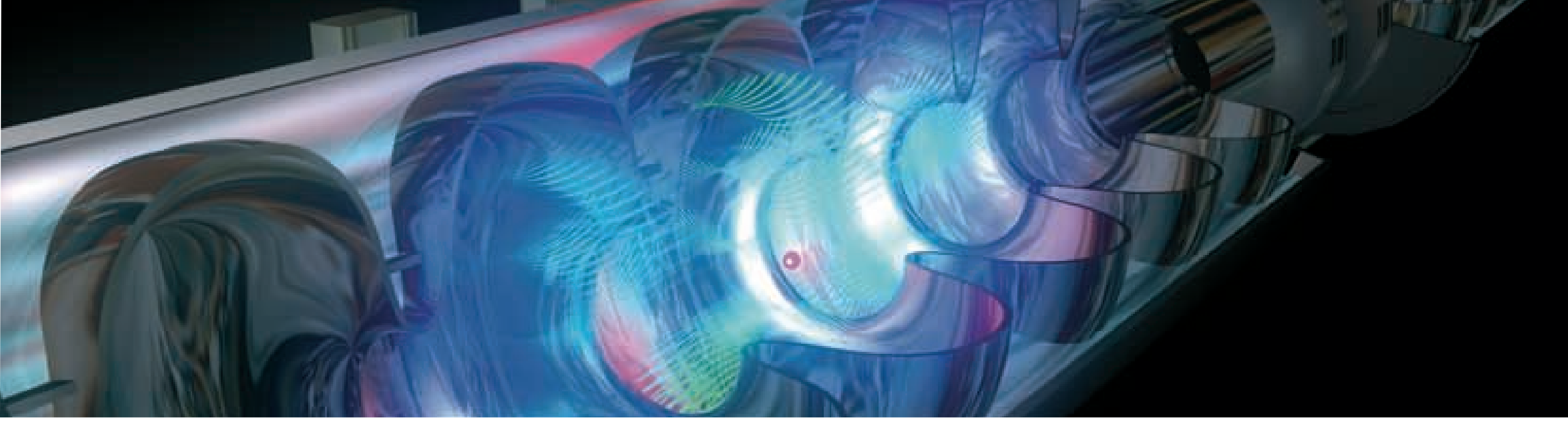
- **Particle physics:**
  Scientists from around the world use accelerators to investigate the fundamental building blocks and forces of the universe.

The spectrum of research at DESY is correspondingly diverse – as is the cooperation with partners both national and international. More than 3000 scientists from over 40 countries come to work at DESY each year.

The research programme is not restricted to the facilities in Hamburg and Zeuthen. Indeed, DESY is closely involved in a number of major international projects, including the European XFEL X-ray laser in Hamburg, the Large Hadron Collider LHC in Geneva, the neutrino telescope IceCube at the South Pole and the International Linear Collider ILC.

DESY facts and figures

- Deutsches Elektronen-Synchrotron DESY
- A Research Centre of the Helmholtz Association
- A publicly funded national research centre
- Locations: Hamburg und Zeuthen (Brandenburg)
- Employees: approx. 2000, including 200 in Zeuthen
- Budget: 192 million euro (Hamburg: 173 million euro, Zeuthen: 19 million euro)



Computer simulation of particle acceleration

Accelerators

The development of particle accelerators involves special challenges for both humans and machines. Time and again it is necessary to push back the frontiers of science and technology. Over more than 50 years DESY has accumulated vast experience of accelerator development and is now one of the world's leading authorities in this field. DESY focuses on two principal areas of research:

- The development of light sources for science with photons in order to enable structures and processes to be observed on extremely small space and time scales. To this end, particles are first accelerated and then deflected by means of large magnetic structures in such a way that they emit a special form of radiation.
- The development of increasingly powerful accelerators for particle physics research in order to accelerate particles to ever greater energies and thereby obtain deeper insights into the very heart of matter and the origin of the universe.

Photon science

The intense radiation generated by particle accelerators can illuminate even smallest details of the microcosm. At DESY scientists from around the world use this light to investigate the atomic structures and reactions of promising new materials and biomolecules that might one day be used to make new drugs. DESY's unique spectrum of light sources makes it one of the world's leading centres for photon science:

- The DORIS III particle accelerator provides radiation suitable for a whole range of experimental purposes. This includes the analysis of catalysts and semiconductor crystals.
- Unique experimental opportunities are offered by the new free-electron laser FLASH, which generates extremely intense short-wavelength laser pulses.
- The world's best storage ring-based X-ray radiation source, PETRA III, provides first-class brilliant X-ray radiation.
- The X-ray laser European XFEL, which is currently under construction, will complement the unique range of light sources in the Hamburg region.

Particle physics

On the trail of quarks, supersymmetry and extra dimensions – particle physicists at DESY inquire into the very structure of our world.

- Using data recorded with the "super electron microscope" HERA, an underground accelerator six kilometres in circumference, scientists investigate the structure of the proton and the fundamental forces of nature.
- Researchers will have unique opportunities to decipher the mysteries of matter, energy, time and space with the next major projects in the field of particle physics, in which scientists from DESY are also participating: the Large Hadron Collider LHC in Geneva, which is the world's most powerful accelerator, and the planned International Linear Collider ILC.
- Using the neutrino telescope IceCube at the South Pole, DESY researchers and their colleagues gaze into the vast expanses of the cosmos in search of ghost particles from space.

Meanwhile scientists in the field of theoretical particle physics are working at DESY to try and piece together the big picture that corroborates the host of experimental findings.

WORLD CLASS.

Cutting-edge research at one of the leading accelerator centres

Over the past 50 years and more, DESY has moved from being a relatively small national research facility to become one of the world's most important centres for particle physics and research with X-ray radiation. The secret behind this success story has been DESY's expertise in the development, construction and operation of large-scale particle accelerators. It is exactly these highly complex pieces of scientific equipment that enable DESY to conduct cutting-edge research.

Serving the research community

When it comes to investigating the smallest building blocks of the physical world, particle accelerators are an indispensable tool. DESY's mission is to provide such facilities for scientists from Germany and throughout the world. As the research centre's statutes in 1959, the year in which it was founded, stated, "The purpose of the DESY foundation is to enable and assist fundamental research in the natural sciences, first and foremost by building and operating particle accelerators and providing for the scientific use thereof, particularly in the field of research with elementary particles and synchrotron radiation as well as research and development related to these activities."

Challenging accelerators

Almost all of the research carried out at DESY – whether in the field of particle physics or with the extremely intense light produced by the accelerators – depends crucially upon the performance and reliability of the accelerator facilities. It should therefore come as no surprise that the Accelerator Division has the highest number of staff at DESY. All in all, around 600 people, divided among 18 groups, work on accelerator development, construction and operation, in close cooperation with universities, research institutions and industrial companies from Germany and throughout the world. To design, build and then successfully run such huge and sophisticated pieces of high-tech equipment over a period of many decades requires the combined forces of numerous experts from a whole range of specialist fields.

A world-class accelerator centre

With over 50 years of experience to its name, DESY is among the world's leading accelerator centres. Very soon after the research centre was founded, the young and still inexperienced team at DESY was nonetheless able to develop and build one of the most powerful electron synchrotrons of the 1960s. The results achieved with this facility established DESY as one of the top international centres in the field of particle physics. At the same time, it laid the foundations of what would prove to be a second and highly fruitful area of research at DESY: the use of particle accelerators as sources of intense light.

The early 1970s saw the construction of DORIS, one of the world's first large storage rings, which to this very day still serves as a reliable X-ray source for research teams from around the globe. In its day, the PETRA storage ring was the largest and most powerful electron accelerator in the world. A masterpiece of accelerator design, it put DESY at the very forefront of particle research with electron-positron collisions from 1978 onwards. Today the facility is back in operation as the world's leading storage ring-based X-ray radiation source.

DESY enjoys a long tradition of international cooperation, not least in the field of accelerator physics. One of the best examples of such collaboration was the construction of the electron-proton storage ring HERA, Germany's largest research instrument to date, which remained in operation at DESY from 1990 to 2007. All in all, 11 countries were involved in the construction project.

Today, over 50 research institutes from 12 countries are involved, under the leadership of DESY, in the development of the pioneering TESLA technology, which is based on superconducting accelerator elements. The FLASH free-electron laser at DESY is the first facility to make use of this ground-breaking technology.

As one of the world's leading centres in this field, DESY is ideally positioned to play a key role in current and future international projects, such as the X-ray laser European XFEL, which is currently under construction in the Hamburg area, and the next major project in the world of particle physics, the planned International Linear Collider ILC.

"Accelerator physics is an extremely vibrant field of research at DESY. Over the past 50 years and more, it has given rise to the development of new and innovative technologies that have continually enhanced the scientific use of the accelerator facilities as well as opening up some entirely new avenues of research."

Dr. Reinhard Brinkmann
DESY Director of the Accelerator Division

PACE SETTER.

High technology for elementary particles

Although particle accelerators were originally developed in order to investigate the smallest building blocks of matter, they are now encountered in a host of other fields. While particle physicists use vast high-energy accelerators to hunt for Higgs bosons or extra dimensions, scientists from many other disciplines – from materials science to molecular biology and medicine – find the radiation generated at accelerator facilities to be an immensely versatile research tool. And smaller accelerators are used in a whole variety of applications, including radiation therapy and chip manufacture.

An accelerator in the living room

Until recently, almost every household possessed a small particle accelerator in the shape of a cathode ray tube. This component of many older TVs contains a spiral-wound filament that emits electrons. These are accelerated by electric fields and deflected by magnetic fields in such a way that they collide with the particle detector – the screen – at a preordained point, thus producing a pixel. Such an electric field exists, for example, between two metal plates with opposing charges. Within this field, a negatively charged particle will be attracted by the positively charged plate and repelled by the negatively charged one, and a positively charged particle will be accelerated in the opposite direction.

There are relatively tight limits to the degree of acceleration that can be achieved with a static electric field, as employed in a cathode ray tube. Particle accelerators therefore use radio-frequency alternating electromagnetic fields, which carry along and accelerate the particles much like surfers riding a wave. Modern accelerators feature multiple acceleration sections that repeatedly feed the particles with energy. In linear accelerators, these acceleration sections are arranged one after another; in ring accelerators, particles pass repeatedly through the same acceleration sections many thousands of times a second. Magnetic fields ensure that the particles are kept on their path around the ring.

Super microscopes

Ever since accelerators were invented in the 1920s, particle physicists have used them to hunt for the smallest building blocks of matter. They have already helped decipher many of the mysteries of what holds the world together at its core. To this end, two basic experimental methods are employed: particles accelerated to high energies are fired at a fixed target; or two high-energy particle beams circulating in opposite directions are collided with one another in a ring accelerator. In accordance with Einstein's equation $E = mc^2$, matter is converted into a flash of energy, which itself gives rise to new and exotic particles in a fraction of a second. These fly off in all directions and are registered by huge detectors installed around the collision point. With their giant experiments, today's accelerators are like incredibly powerful microscopes that provide researchers with an insight into the smallest particles of matter and the forces that hold them together.

One important measure of accelerator performance is the maximum achievable particle energy. The higher the energy, the smaller the structures of matter that can be investigated. However, there are technical limits to the particle energies that can be achieved. Whenever electrically charged particles such as electrons travel along a curved path, they emit so-called synchrotron radiation. As a result, they lose energy, which has to be restored by means of further acceleration. Even in storage rings, where the particle beams circulate for hours on end, the particles have to be continually accelerated in order to offset these energy losses. This imposes a limit on the maximum particle energy achievable in a ring accelerator. For this reason, the International Linear Collider ILC, one of the next major projects in the world of particle physics, is based on two linear accelerators facing each other.

Light sources

As far as particle physics is concerned, the synchrotron radiation produced in ring accelerators is nothing but a nuisance. Pretty soon after its discovery, however, scientists recognized its huge experimental potential in a wide range of fields such as physics, chemistry, geology, biology, materials science and medicine. Indeed, what was originally troublesome interference rapidly proved to be a real research hit. Today there are some 50 particle accelerators in operation as synchrotron radiation sources worldwide, and around 40 000 scientists are currently using this exceptional light to investigate a whole variety of materials – a trend that is increasing. The development of new and internationally competitive radiation sources is therefore high on the list of priorities at accelerator centres.

In today's storage ring-based light sources, synchrotron radiation is no longer generated only by means of the bending magnets used to hold the particles on their course, but also by means of additional metre-long special magnetic structures. These so-called wigglers and undulators consist of series of alternating north and south magnetic poles. When electrons travelling at the speed of light race through this sequence of magnets, they are forced to follow a slalom course. This causes them to emit a much more intense beam of light than is produced with a single bending magnet. High-intensity radiation of an entirely new quality is produced by the light sources of the next generation, the free-electron lasers (FEL). This FEL radiation has the properties of laser light and is generated in ultra-short pulses, which creates unique experimental opportunities.

Highly versatile

Of the 17 000 or so particle accelerators currently in operation worldwide, only around 100 are used for fundamental research in nuclear and particle physics – the purpose for which they were originally developed. Accelerators in the mid- and low-energy ranges today perform valuable service in a host of applications ranging from medicine to the food industry.

In hospitals, for example, linear accelerators are used for both radiotherapy and radiosurgery. Today there are around 200 accelerators in operation worldwide for the production of radioisotopes for diagnostic purposes, and as many as 7500 for use in radiotherapy. Disposable medical equipment is sterilized using radiation from particle accelerators. Food, too, can be preserved in the same way: depending on the dosage, ionizing radiation is used to fight parasites and pests, increase shelf life and kill germs. Electron beam welding, which employs a beam of accelerated electrons to join workpieces, is used in the mass production of transmission components for the automotive industry and also in the production of components for the aerospace, rail and food industries. The photomasks used in chip manufacture are produced by means of electron beam lithography, which requires an electron beam generated in a particle accelerator. There are also plenty of highly promising applications in the pipeline. In the future accelerators could, for example, be used to dispose of radioactive waste.

Principle of a particle accelerator

Focusing magnet

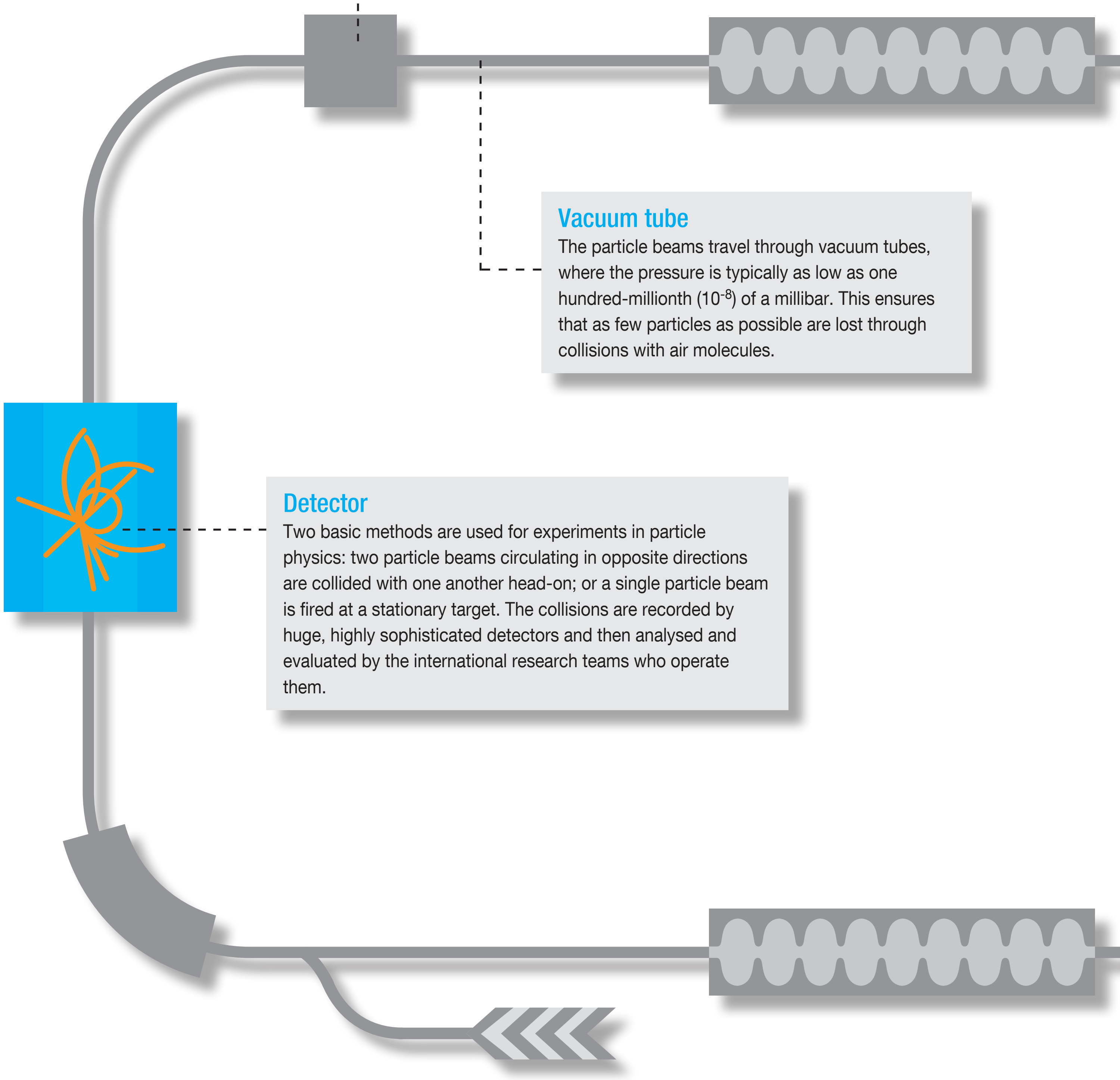
A particle beam is made up of small "bunches" composed of particles all bearing the same charge. Since the individual particles are not all travelling in exactly the same direction, the bunches tend to disperse over longer distances. To prevent this from happening, they pass through focusing magnets (quadrupole magnets) placed at regular intervals. These generate a field like a magnetic lens, which forces the particles to reconverge into a tight bunch.

Vacuum tube

The particle beams travel through vacuum tubes, where the pressure is typically as low as one hundred-millionth (10^{-8}) of a millibar. This ensures that as few particles as possible are lost through collisions with air molecules.

Detector

Two basic methods are used for experiments in particle physics: two particle beams circulating in opposite directions are collided with one another head-on; or a single particle beam is fired at a stationary target. The collisions are recorded by huge, highly sophisticated detectors and then analysed and evaluated by the international research teams who operate them.

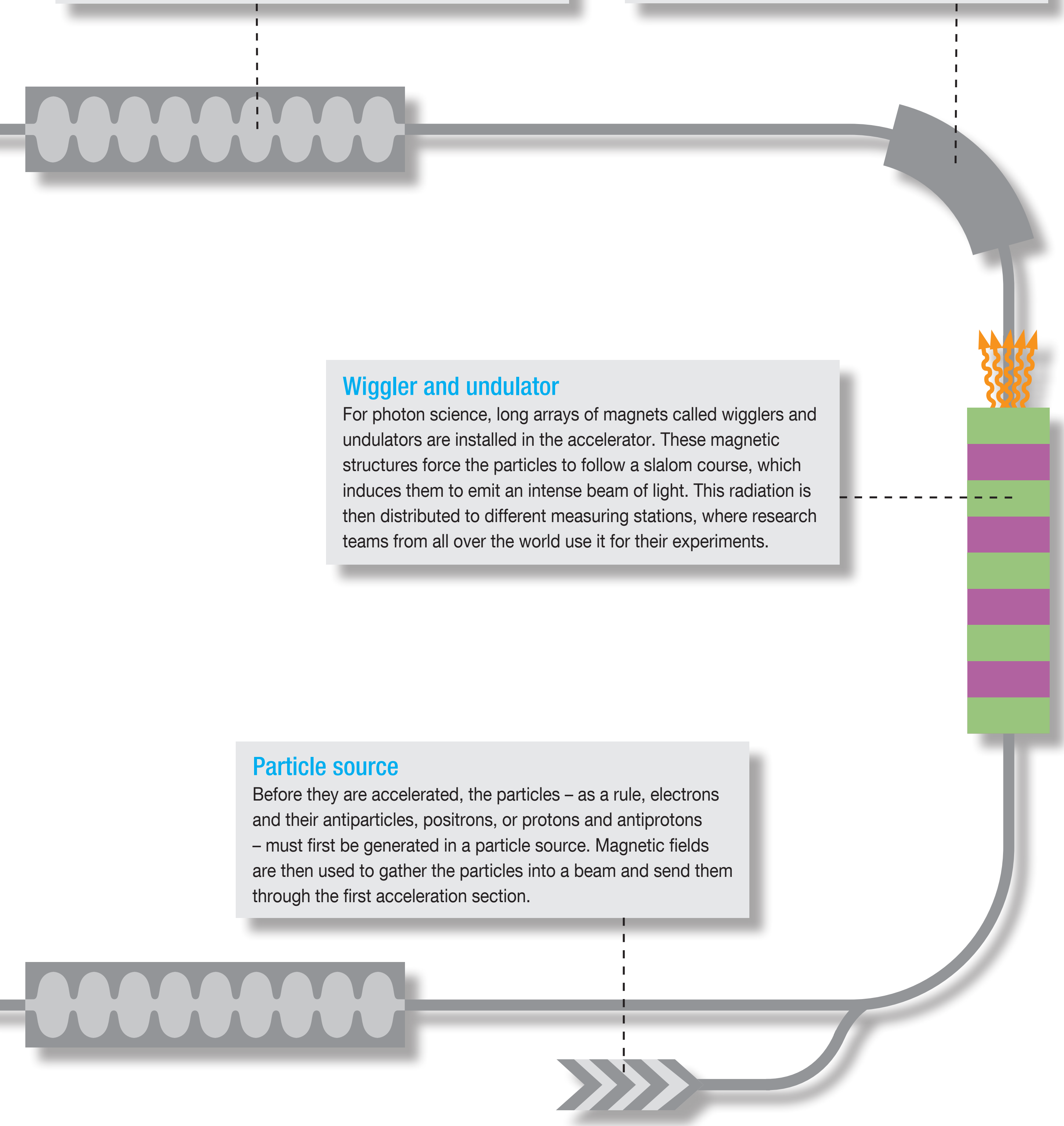


Acceleration section

The particles are boosted to their requisite velocity in the acceleration sections. In ring accelerators and long, high-energy linear accelerators, cavity resonators are used for this purpose. The radio-frequency electromagnetic fields oscillating in these cavities are synchronized in such a way that the particles continuously pass through a field with the appropriate polarity and are therefore carried along and accelerated much in the manner of surfers riding a wave.

Bending magnet

Inside a ring accelerator or when travelling between two accelerators, the particles are held on course by deflecting or bending magnets. These are dipole magnets whose magnetic fields force the particles to follow a curved path.



Wiggler and undulator

For photon science, long arrays of magnets called wigglers and undulators are installed in the accelerator. These magnetic structures force the particles to follow a slalom course, which induces them to emit an intense beam of light. This radiation is then distributed to different measuring stations, where research teams from all over the world use it for their experiments.

Particle source

Before they are accelerated, the particles – as a rule, electrons and their antiparticles, positrons, or protons and antiprotons – must first be generated in a particle source. Magnetic fields are then used to gather the particles into a beam and send them through the first acceleration section.

TRAIL BLAZER.

Particle accelerators at DESY

As one of the world's leading accelerator facilities conducting research into the fundamental structures of matter, DESY has been developing, building and operating large-scale particle accelerators for over 50 years. These accelerators are used in two particular fields: photon science, where they serve as sources of brilliant light to investigate a wide range of samples; and particle physics, where they are used as incredibly powerful microscopes that enable researchers to investigate the fundamental building blocks of matter and the forces that hold them together.

Light sources for photon science

In order to conduct research with photons (particles of light), special light sources are developed. Using the radiation they produce, it is possible to observe structures and processes on extremely small space and time scales. To this end, particles are first accelerated and then deflected by long magnetic structures in such a way that they emit a special form of radiation.

With its diversity of light sources, DESY is one of the world's leading locations for photon science. As a rule, similar research institutions just have one light-producing accelerator, which is set up to provide specific radiation properties. In contrast, at DESY both the existing and the future light sources complement one another perfectly. The tried and tested synchrotron radiation source DORIS III provides millimetre-sized beams of light with a high photon flux. The world's most brilliant storage ring-based X-ray radiation source – PETRA III – generates intensive radiation, whose spectrum extends well into the hard X-ray region. The free-electron laser FLASH provides extremely intense, ultra-short laser pulses in the ultraviolet and soft X-ray region. What's more, starting in 2014 the X-ray laser European XFEL, which is currently being realized as a European project with strong DESY participation, will generate extremely brilliant flashes of laser light in the hard X-ray region. With all these

light sources, the scientists working at DESY have access to exactly the type of radiation they require for their experiments – a decisive competitive advantage for photon science in Europe.

Super microscopes for particle physics

Increasingly powerful accelerators are being developed for particle physics research in order to accelerate particles to ever greater energies and thereby obtain deeper insights into the very heart of matter and the origin of the universe.

Until 2007, large high-energy accelerators were being used to conduct particle physics experiments at DESY – most recently, the unique super electron microscope HERA. As in astronomy, where researchers from all over the world work with just a few telescopes that are constructed and operated by international collaborations, the focus of particle physics today is shifting to a few large-scale facilities that can no longer be sustained by one country alone. Instead, such facilities can only be realized as broad-based international projects.

This type of international cooperation enjoys a long tradition at DESY. That's why the particle physicists at DESY contribute their knowledge at a number of such large-scale international facilities. In particular, they participate in the experiments at the world's most powerful accelerator, the Large Hadron Collider LHC in Geneva, and contribute substantially to the development of the planned linear accelerator of the future: the International Linear Collider ILC.

Technological development

Developing the accelerator technology for the next major particle physics project – the International Linear Collider ILC – represents a special challenge. Working together with international partners, DESY has developed and tested the TESLA technology, which is based on superconducting accelerator modules. The global community of particle physicists has resolved to use the TESLA technology for the ILC. What's more, this accelerator technology can also be used to operate new types of X-ray laser. The first light source of this kind is the free-electron laser FLASH at DESY. The X-ray laser European XFEL is currently under construction.

In Zeuthen, DESY operates the Photo Injector Test Facility PITZ, which is used to develop and optimize special electron sources that will be needed by the new generation of free-electron lasers.

The boundaries of what is technically possible are constantly being pushed back as developers continue to improve the performance of accelerator facilities. DESY's cooperation with industrial companies leads to important innovations not only in areas such as electronics and radio-frequency, vacuum and refrigeration technology but also when it comes to operating complex superconducting systems.

50 years of particle accelerators at DESY

For more than half a century, DESY has been developing, building and operating large particle accelerators. Most of them were used in various incarnations for different research purposes – the hunt for the smallest building blocks of matter in particle physics and the multi-faceted investigations using brilliant light in the field of photon science. When, after decades of use, one of the accelerators was no longer up to the demands of top-level research, it was by no means made redundant. Instead, it then became a pre-accelerator for a larger facility or provided test beams for the development of subsequent projects.

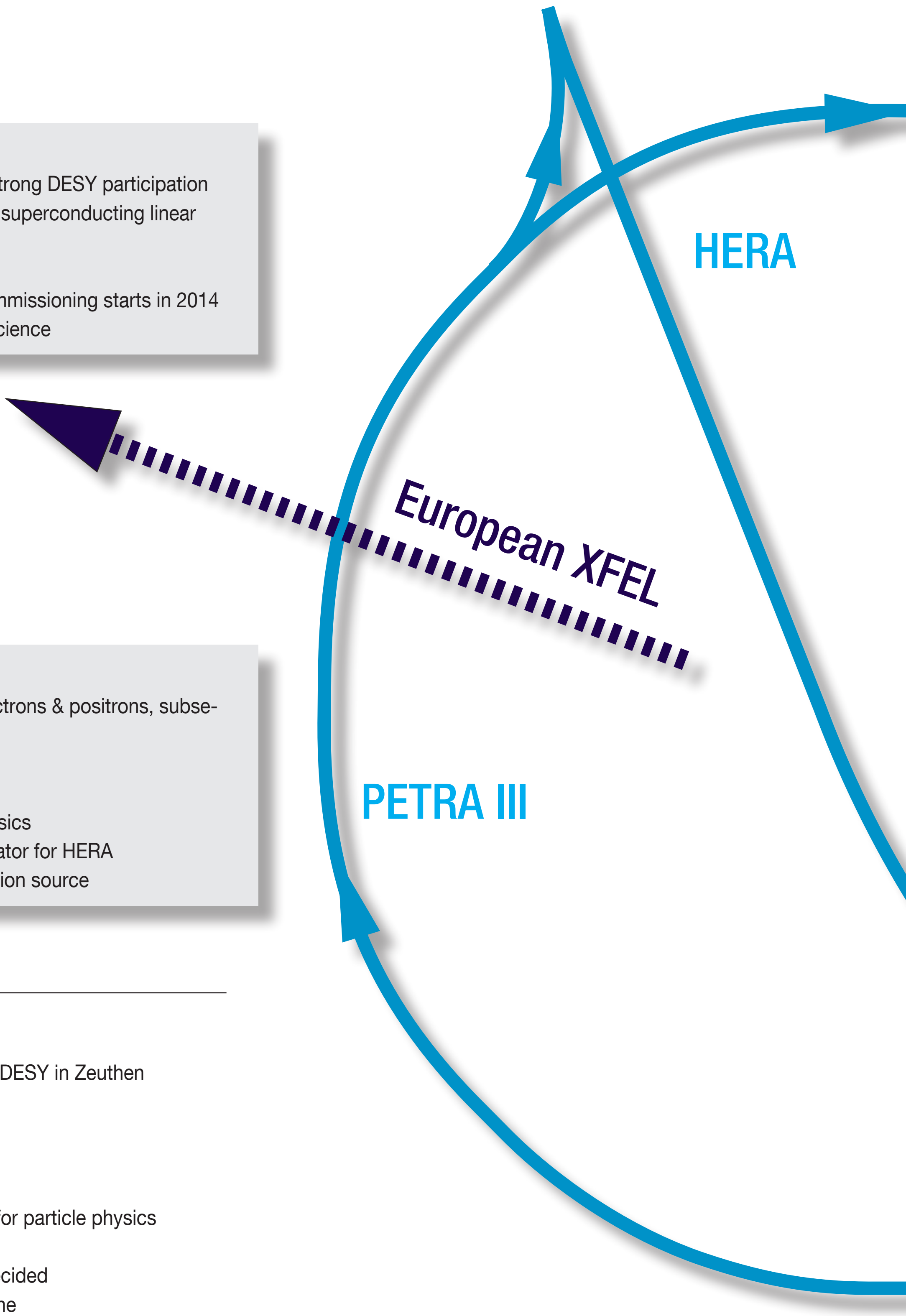
For example, the longest-serving accelerator – the German electron synchrotron "DESY" that gave the centre its name – operated for 43 years, from 1964 until 2007: first for particle physics, then in parallel for photon science and finally, from 1987 on, as a pre-accelerator for the storage ring HERA.

Installation of a superconducting accelerator module in the free-electron laser FLASH

Accelerators at DESY

HERA
- Electron-proton storage ring for particle physics
- Length: 6336 m
- Research operation: 1992 to 2007
- Evaluation of the data is continuing
- Experiments: H1, ZEUS, HERMES, HERA-B

European XFEL
- European project with strong DESY participation
- Free-electron laser with superconducting linear accelerator
- Length: approx. 3.4 km
- Under construction, commissioning starts in 2014
- X-ray laser for photon science



PETRA III
- Ring accelerator for electrons & positrons, subsequently also for protons
- Length: 2304 m
- Commissioning: 1978
- 1978-1986: particle physics
- 1987-2007: pre-accelerator for HERA
- Since 2009: X-ray radiation source

PITZ
- Test stand with linear accelerator at DESY in Zeuthen
- Length: approx. 12 m
- Commissioning: 2002

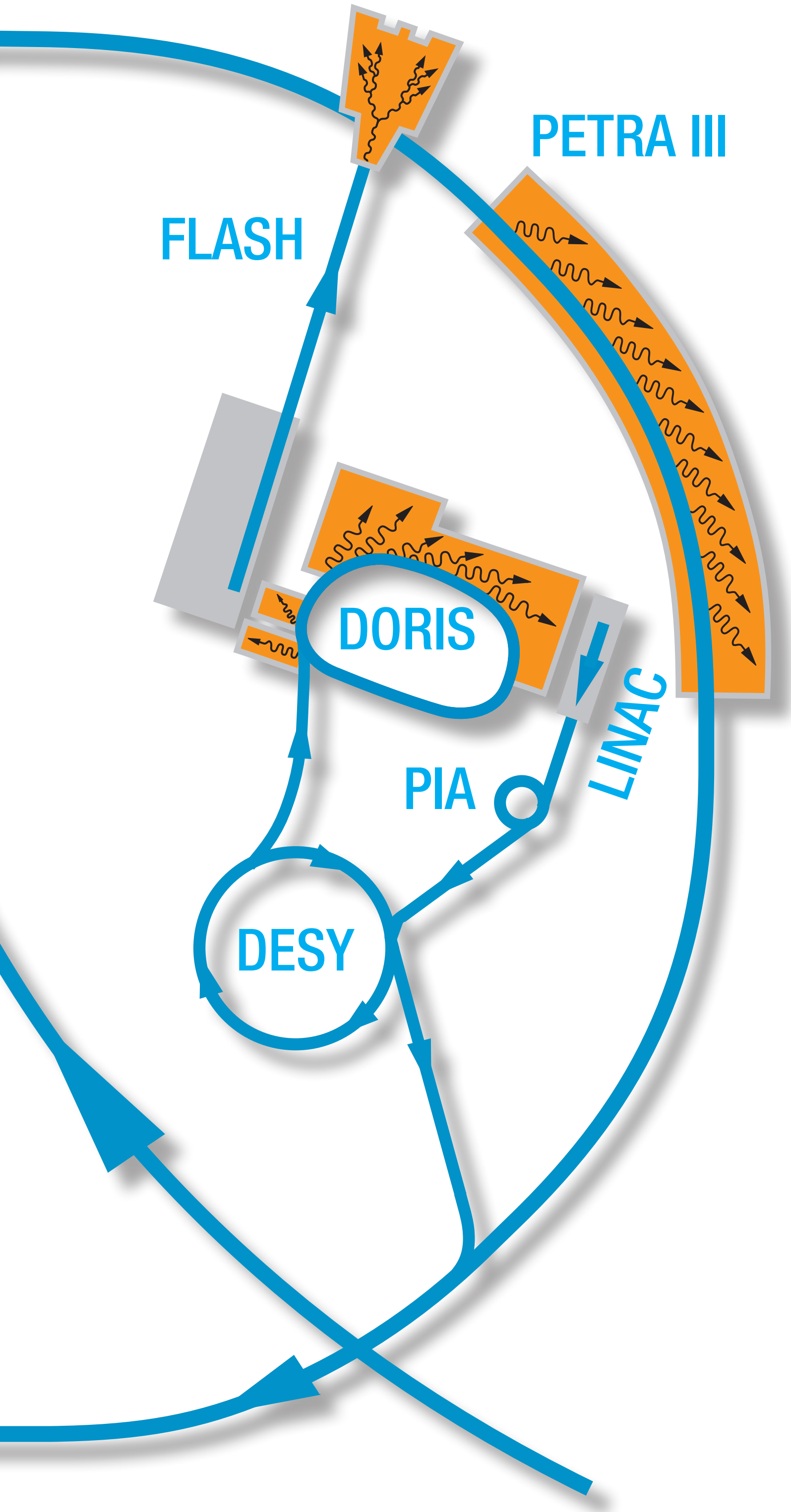
ILC
- Electron-positron linear accelerator for particle physics
- Length: approx. 35 km
- Being planned, location still to be decided
- Two experiments at one collision zone

FLASH

- Free-electron laser with superconducting linear accelerator
- Lenght: 260 m
- 1992-2005: test facility for accelerator and FEL technology
- Since 2005: photon science

DORIS III

- Ring accelerator for electrons & positrons
- Length: 289 m
- Commissioning: 1974
- 1974-1992: particle physics and research with synchrotron radiation
- Since 1993: synchrotron radiation source



LINAC II

- Linear accelerator for electrons & positrons
- Length: 70 m
- Commissioning: 1971
- Pre-accelerator

LINAC III

- Linear accelerator for protons
- Length: 32 m
- Commissioning: 1988, decommissioning: 2007
- Pre-accelerator

PIA

- Accumulator for electrons & positrons
- Length: 29 m
- Commissioning: 1979
- Pre-accelerator

DESY I/III

- Ring accelerator for electrons & positrons; for protons as of 1987
- Length: 317 m
- Commissioning: 1964, decommissioning: 2007
- 1964-1978: research operation
- From 1973: pre-accelerator

DESY II

- Ring accelerator for electrons & positrons
- Lenght: 293 m
- Commissioning: 1987
- Pre-accelerator

DEVELOPMENT

From national accelerator laboratory to world-class institution

First record machine

As the founders of DESY were working out their plans for the new particle physics research centre in the mid-1950s, they weren't interested in half measures. A ring-shaped accelerator of the synchrotron type was to be built in Hamburg. It would have a diameter of 300 metres and accelerate electrons to an energy of 6 billion electronvolts (gigaelectronvolts, GeV). That represented a new record and the highest energy researchers could hope to reach at that time with an electron synchrotron. Such a machine would optimally complement the proton accelerators of the day, which were under construction at CERN in Geneva and in the USA.

It was by no means inevitable that this first particle accelerator at DESY would quickly be operational and that no major problems would arise. The young physicists and engineers brought together at the time by DESY Director Willibald Jentschke were extremely dedicated, but most of them lacked experience in the field of accelerator construction. Fortunately, they were able to draw on the expertise of accelerator designers in the USA and Geneva, and compensated for their inexperience with tremendous

enthusiasm. In the end, the young DESY team managed to realize one of the most powerful electron synchrotrons built in the 1960s. Their success was largely due to the excellent leadership of DESY Director Willibald Jentschke. He ensured that tolerance and solidarity were hallmarks of DESY right from the very beginning. Over the years, this spirit has brought DESY many further successes and still characterizes the research centre today.

Triumph of the storage rings

At the end of the 1960s, a courageous decision was once again taken at DESY. Instead of replacing the first synchrotron with a larger accelerator of the same type, those responsible at DESY decided to back a very promising, but nonetheless young and immature technology. The next accelerator was to be a storage ring. This is a type of accelerator facility in which the particles circulate for hours and collide head-on in flight at specific locations. The great thing about the new concept was that it enables significantly higher collision energies to be reached than is possible with a beam directed at a stationary target. The DESY accelerator team mastered this risky task admirably. After many years of operation as a collider, the DORIS storage ring – currently in its third expansion phase – is still in service, nowadays as a high-performance light source.

After the first, extremely successful, positive experience with the new type of accelerator, it became clear that the next facility to be constructed at DESY should also be a storage ring. What's more, it was to be the largest of its kind in the world. With a circumference of 2.3 kilometres, PETRA achieved a collision energy of 38 GeV. Later it even managed 47 GeV – around five times the level achieved by the generation of accelerators that preceded it. The DESY accelerator team broke all the pertinent records during the construction phase. In July 1978, less than three years after approval had been granted for PETRA, the first electrons were circulating inside the ring. The PETRA construction engineers had finished more than one year ahead of schedule and required 20 million deutschmarks less than planned. This head start on the rest of the world was to pay off. Just one year later, the physicists at PETRA tracked down the gluon

– the “glue” particle that holds the quarks together. This discovery finally established DESY’s position at the leading edge of research worldwide.

In the 1980s the Hamburg research centre once again took on a pioneering role in totally new territory with the construction of DESY’s largest accelerator, the 6.3-kilometre-long HERA storage ring accelerator. It wasn’t just that HERA was to be the first and only facility in the world in which different types of particle – electrons and protons – were fired at one another. The extremely demanding technology of the superconducting magnets that kept the protons on their curved path also had to be specially developed. And that wasn’t the end of the story. Back then, nobody else worldwide had ventured to build such a large accelerator under a city’s residential neighbourhoods. Taken together, these factors meant that HERA was the biggest and most difficult undertaking that DESY had ever attempted. The concept, however, worked. For fifteen years, HERA functioned extremely reliably as a “super electron microscope”, delivering a vast quantity of data on the interior of the proton and the forces acting there.

International connections

The construction and operation of the storage ring PETRA in the mid-1970s also marked an important development that was to profoundly influence the work of DESY and the other accelerator institutes worldwide: the increasing international scope of particle physics projects – a trend that has been growing ever since. At the time, the particle collisions at PETRA were observed by a few hundred physicists with the help of five large detectors, which were distributed around the ring. Only a small number of these researchers were DESY employees. Most of them were from institutes and universities in Germany, but also from China, England, France, Israel, Japan, the Netherlands, Norway and the USA. A new aspect was that each team was entirely responsible for the construction, operation and financing of its detector. In return, they were largely free to act independently. This concept has meanwhile become popular in many other particle physics projects.

In the 1980s the construction of HERA at DESY became a perfect example of successful international collaboration. A total of 11 countries contributed to the effort – a milestone for particle physics. Previously, detectors had been built in international cooperation, but accelerators had been the preserve of the host institute. In contrast, international interest in HERA was so great that numerous renowned institutes from countries abroad – including Canada, France, Israel, Italy, the Netherlands, the United Kingdom and the USA – sent personnel and constructed important parts of the accelerator. Italy alone delivered around half of the 400 superconducting bending magnets. More than 20 per cent of the accelerator was thus financed from outside Germany. The corresponding figure for the four HERA experiments, which were operated as usually by large international teams of physicists from all over the world, was around 60 per cent. This “HERA model” of international cooperation functioned so well that it became the role model for large international research projects.

Accelerator construction today – a global undertaking

This national and international networking, which was built up over decades, continues to benefit DESY now that HERA has been switched off. This is because the large-scale projects of particle physics are now so complex and expensive that they can only be implemented and operated in large collaborations involving many institutes, universities and research centres distributed around the world. This situation leads to new forms of cooperation on the national and international levels.

One example is the Helmholtz Alliance "Physics at the Terascale" initiated by DESY, which is made up of all of the German universities and institutes collaborating on experiments at the LHC proton collider in Geneva and on the planned linear accelerator ILC. The common goal of the partners in the alliance is to bring together and, in the long term, enhance the expert knowledge in particle physics at German research institutions. DESY is also contributing substantially to the activities of the alliance in the area of accelerator development, by making available the comprehensive expertise of its employees and its important infrastructure.

On the international scene, DESY is an increasingly sought-after partner when it comes to accelerator construction. At the start of the 1990s the international TESLA Collaboration (now known as the TESLA Technology Collaboration) formed under the leadership of the research centre to draw up a concept for the next major future particle physics project: an electron-positron linear collider. And the effort was worthwhile. The superconducting accelerator technology developed by the TESLA Collaboration was chosen as the basis of the planned linear accelerator ILC in 2004. This means that DESY is one of the key players regarding the development work for the ILC – a project in which more than 2000 scientists from over 300 universities and institutes in more than 25 countries are participating.

What's more, the superconducting TESLA accelerator technology has also found its way into two of the latest-generation light sources, which are also being realized and used in a broadly based international collaboration. These are the free-electron laser FLASH at DESY and the X-ray laser European XFEL, which is currently under construction. Twelve countries are currently collaborating on the latter project in addition to Germany, which is represented by DESY. One of DESY's tasks here is to coordinate the international consortium of 17 institutes which is responsible for constructing the heart of the X-ray laser facility – the almost two-kilometre-long accelerator complex.

Accelerator module in the tunnel of the FLASH free-electron laser

INTERPLAY

Challenge high-energy accelerators

High-energy accelerators are complex high-technology facilities that in some cases have colossal dimensions. Their technology stretches the limits of what is possible, and it usually has to be specifically developed for the project in question. The design, construction and successful operation of such sophisticated machines over many years requires perfect cooperation between hundreds of specialists from an extremely diverse range of fields. Almost 600 people successfully work in this manner at DESY in close cooperation with universities, research institutes and industrial companies from Germany and around the world.

A challenge of the highest order

When you consider how often the coffee machine in the office breaks down or the lawnmower at home gives up the ghost, you realize just how much the construction and successful operation of a high-energy accelerator over many years is akin to a technical miracle. DESY's largest accelerator, the HERA storage ring, consisted of two accelerator rings, each 6.3 kilometres long, which were arranged with a precision of fractions of a millimetre on top of one another in an underground tunnel. The facility was equipped with more than 800 bending magnets, 1340 focusing magnets, 1200 power supply units and 1500 vacuum pumps, all of which were operated and controlled via cables extending for kilometres.

As if that weren't enough, all high-energy accelerators require a complex system of smaller pre-accelerators, which in HERA's case amounted to six. The largest of these, PETRA II, had a circumference of 2.3 kilometres and a correspondingly large number of individual components. And it's not just the machines themselves that are so complex; the interplay between them must be precisely reliable down to fractions of a second and millimetre. That's the only way to ensure that the hair-thin particle beams collide as they should at the centre of the particle physics detectors, and that the more than 2000 guest researchers from all over the world who utilize DESY's light sources each year are provided with precisely the radiation they need for their experiments.

Accelerator experts at DESY

When DESY was founded in 1959, its statutes included the provision that the organization should make available large-scale accelerator facilities as a service for particle physicists and synchrotron radiation researchers from Germany and around the world. What began on a small scale back then has now taken on huge dimensions, and today DESY employs around 600 men and women divided into a total of 18 specialist groups that work on the development, construction and operation of accelerators. DESY's Accelerator Division is thus the organization's largest in terms of employees, which makes sense, since the tremendous challenges in this area can only be met through the combined knowledge and dedication of numerous experts from an extremely wide range of fields.

What does it take?

A total of 18 specialist groups are responsible at DESY for the construction and operation of particle accelerators.

Diagnosis and Instrumentation -MDI-

- Measurement of the beam properties in nearly all accelerators at DESY

Construction of Accelerators and Experiments -MEA-

- Technical project planning for new accelerators and experiments
- Maintenance of existing facilities

Radiation Protection -D3-

- Implementation of applicable laws, including the Radiation Protection Ordinance and the X-Ray Ordinance, as well as compliance with government permits and restrictions

Accelerator Operation -MBB-

- Operation of all DESY accelerators in shifts, 24 hours a day, seven days a week
- Rapid diagnosis and repair in the event of a fault

Radio-Frequency Technology -MHF-

- Development and operation of all radio-frequency facilities at DESY
- Development and construction of the radio-frequency system for the X-ray laser European XFEL with the participation of technical groups from Zeuthen

Injection / Ejection -MIN-

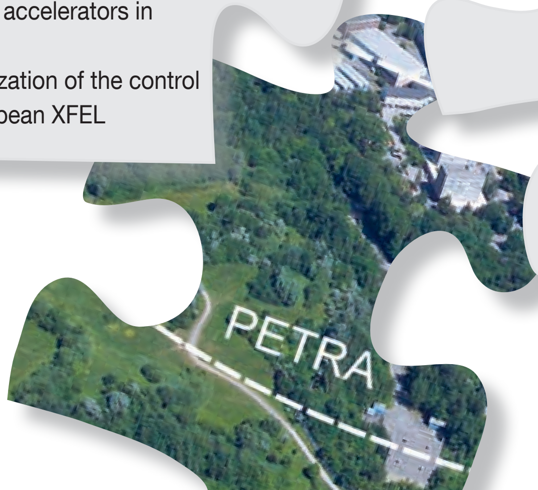
- Operation and refinement of LINAC II and PIA
- Beam transport to DESY II
- All injection and ejection elements
- Coordination of the operation of FLASH

Control Systems -MCS-

- Operation and refinement of the control systems for all DESY accelerators in Hamburg
- Conception and realization of the control systems for the European XFEL

Personal Safety Systems -MPS-

- Safety systems for protecting individuals from ionizing radiation
- Safety systems for magnet current operation



Cryogenics and Superconductivity -MKS-

- Development of cryogenic and superconducting technology, in particular for FLASH and the European XFEL
- Cryogenic helium supply for FLASH and numerous test facilities at DESY, in the future also for the European XFEL

Vacuum -MVS-

- Vacuum systems for all accelerators at DESY in Hamburg
- Accelerator vacuum systems for the European XFEL

Beam Control -MSK-

- Control and instrumentation tasks in connection with beam dynamics in all accelerators at DESY

Accelerator Physics -MPY-

- Development, operation and improvement of all accelerators at DESY
- Studies in beam and FEL physics

Accelerator Coordination -MDE-, -MDO-, -MPE-

- Coordination of the operation of DESY II, DORIS III and PETRA III

Machine Planning -MPL-

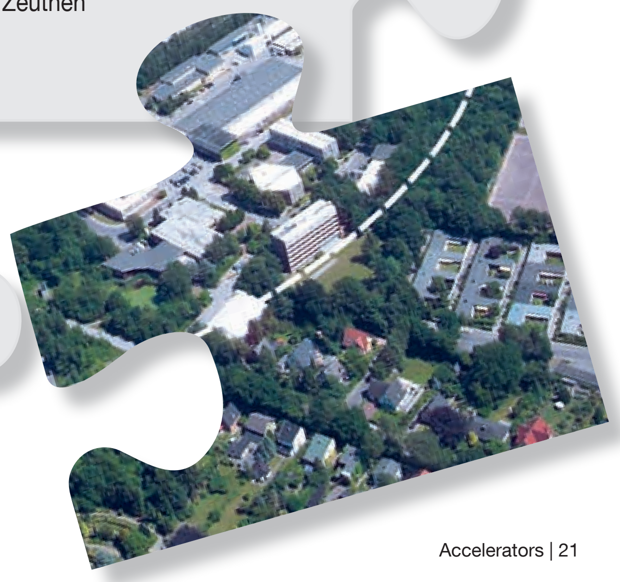
- Calculation, design and production documents for various accelerators at DESY
- Material studies and supervision of the production of superconducting cavities

-PITZ-

- Operation and refinement of the Photo Injector Test Facility in Zeuthen

Energy Supply -MKK-

- Energy supply for all accelerators and buildings at DESY
- Supply of electricity for magnets and transmitters
- Water cooling, cold water and pressure generation
- Heating and ventilation



TRANSFERS

Transferring technology to industry

The construction of powerful accelerators for cutting-edge research is a huge technological challenge. The required devices and techniques are often so sophisticated that the accelerator experts first have to design and develop them themselves. The scientists, engineers and technicians at DESY conduct this pioneering work in close cooperation with external specialists and industrial firms. In many cases this work leads to veritable paradigm shifts in areas such as electronics, radio-frequency engineering, vacuum and refrigeration technology, and the operation of complex superconducting systems, with far-reaching possibilities for applications in other fields such as medicine and materials research.

The challenge of continuously pushing the boundaries of technology in collaboration with DESY is also prompting the participating industrial companies to engage in innovative development work and learn new techniques that they can subsequently transfer to other areas. In this way, the developments triggered by DESY's basic research lead to numerous practical innovations that open up new fields of business for industry. Last but not least, the physicists, technicians and computer scientists who switch to the private sector after having been trained at DESY provide companies with decisive new ideas.

Innovations from basic research

One of the most important developments that DESY has worked on in cooperation with international research and industrial partners is the superconducting TESLA accelerator technology, which serves as the basis for the free-electron lasers FLASH and European XFEL as well as the ILC linear accelerator. As part of a study of the economic impact of the European XFEL, the Institute of Allocation and Competition at the University of Hamburg surveyed 57 companies involved in supplying equipment for the TESLA test facility at DESY, where the pioneering TESLA technology was originally developed and tested. The results showed that the development work paid off for the companies in a number of ways:

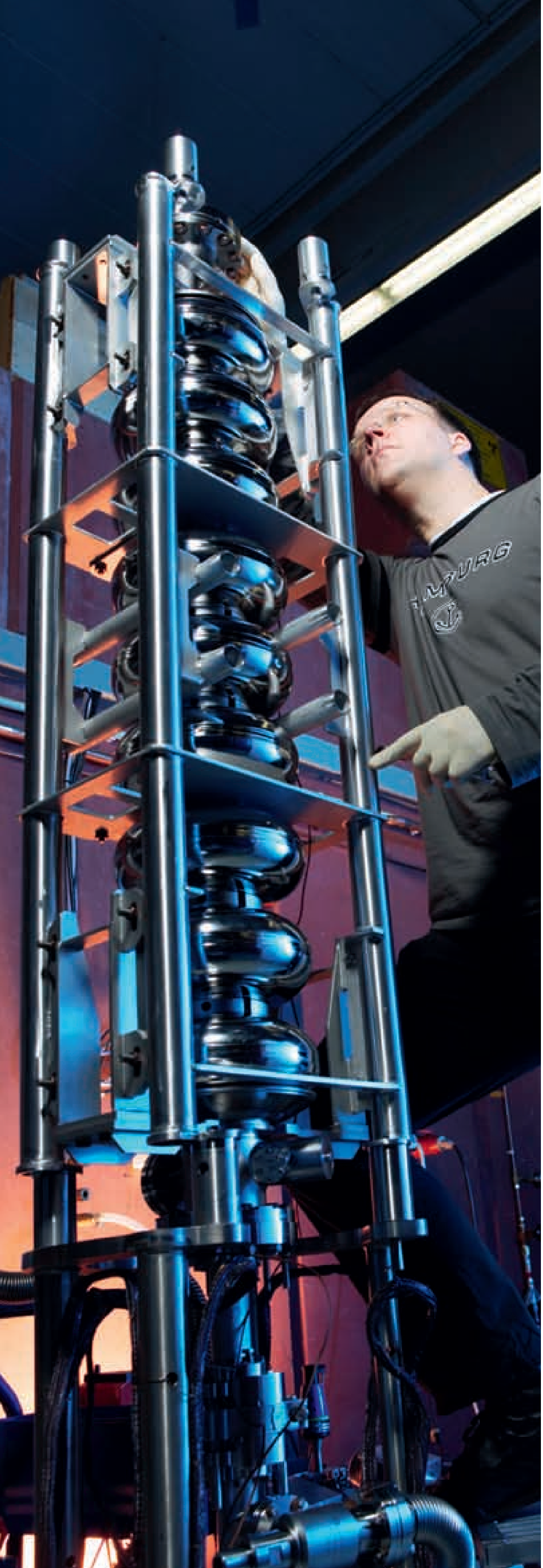
- A total of 67% of the companies developed new products, processes or services as a result of their cooperation with DESY.
- 38% of the companies achieved “significant” or “very significant” innovations as a result of the collaboration, while an additional 29% achieved “mid-level” innovations.
- 79% of the companies also succeeded in finding additional customers for these products or expect to do so.
- 60% of the companies stated that the collaboration has also influenced the rest of their product range, especially in terms of improving product quality and reducing the cost of development, production and maintenance.
- 82% of the companies stated that DESY is an important reference customer for them. On average, the creation of innovations was the most important aspect of their cooperation with DESY – even more important than the generation of revenue.

Further developments were achieved in the areas of radio-frequency technology, electronics, power engineering and pulse-power technology. Another area in which advances were made is refrigeration technology, as the superconducting particle accelerators for the free-electron lasers operate at minus 271 degrees Celsius. The composites developed for this purpose are very resistant to radiation and can also be used for other applications. The construction of the accelerator components produced innovations in mechanical production processes, chemical process engineering, metallurgy, mechanical engineering and measurement and control technology. The new findings are being used in areas such as medical technology, analytics, radar and satellite systems, communications technology and the construction of chemical plants.

A unique opportunity for industry

Construction of the European XFEL is now well under way, and series production of the accelerator components has therefore commenced as well. The European X-ray laser will be the first facility to employ the TESLA technology on a large scale. More than 800 superconducting resonators have to be manufactured for the accelerator under the cleanest conditions possible. They will then be combined with numerous other components produced by research institutes and industrial firms from all over the world to create 100 accelerator modules that will speed up the European XFEL's particle beam.

For years, the teams at DESY have therefore been transferring their superconducting technology expertise and assessing how the manufacturing process can be simplified and improved for series production. The involvement of industry in the development work early on is now paying off. The outstanding position that European scientific institutes and industrial firms occupy in this area is further strengthened and expanded by supporting measures such as the ElFast European industry forum for superconducting accelerator technology, which DESY initiated back in 2005. This provides European industry with a unique opportunity to gain exclusive superconducting technology expertise that ideally qualifies it for additional large-scale projects, such as the 35-kilometre-long ILC with its nearly 2000 accelerator modules.



STRONG TIES

Close cooperation with the University of Hamburg

From its foundation, DESY has always had especially strong ties to the University of Hamburg, also in the field of accelerator physics. As might be expected, this brings numerous benefits for both sides. For those studying, it provides access to opportunities that are unique worldwide. Even at undergraduate level, many students have a chance to experience at close quarters the construction and operation of world-class large-scale accelerator facilities. In the process, they not only have the support of the responsible professors from the University of Hamburg but can also obtain advice and assistance from the accelerator experts at DESY. In many cases, students are given responsibility for important sections. These are chosen with care, so as to ensure that they not only profit from the practically oriented experience but also acquire the soft skills that are so important today. They learn how to work in an independent, accountable and results-oriented way in an international environment.

Thanks to the broadly based training, the detailed insight into the working methods of the technical groups at DESY and the wide variety of international contacts, graduates can look forward to outstanding career opportunities, not only at the world's major accelerator centres but also in industry. This is well documented by the impressive number of national and international prizes that have been awarded to Hamburg graduates in this area over recent years.

By the same token, DESY profits greatly from its close ties to the University of Hamburg, since not only are the students highly motivated, but they also bring new ideas and a breath of fresh air to the research centre. In this way, DESY also contributes more than many other large institutes to ensuring a continuous supply of the kind of highly qualified personnel that are in such demand on today's highly competitive labour market.

By and large, the projects arising from DESY's partnership with the University of Hamburg concern new lines of scientific inquiry and approaches that extend beyond the day-to-day operations of the research centre but which are nonetheless closely connected to existing or planned accelerator facilities at DESY. In the past, such projects concentrated largely on the development of superconducting accelerator components with the highest possible field strengths (see page 48). Meanwhile, however, the focus has shifted to the extreme challenges involved in constructing the free-electron lasers – a new type of light source in which electrons are accelerated to extremely high energies in order to generate intense ultra-short pulses of laser light. ●

UP TO SPEED.

Warming up with the DESY synchrotron and other pre-accelerators

The accelerator control room is the nerve centre of DESY from which all the various accelerators at the research centre are controlled. It requires several stages to accelerate the particles to practically the speed of light. This process takes place step by step in a complex system of pre-accelerators that includes almost every accelerator constructed over the more than 50 years of DESY's history.

Eight accelerators for HERA

Like a car moving up through the gears until it is travelling at top speed, the particles are first accelerated by degrees in a series of smaller pre-accelerators before being fed into the final accelerator, where they are boosted to their intended final energy. If different types of particle are used, as was the case with the electron-proton storage ring HERA, the largest of the DESY accelerators, these have to be pre-accelerated in separate systems. All in all, this can add up to a lot. In the case of HERA, for example, eight different accelerators were used to propel the electrons and protons to the high energies required for the kinds of experiment being conducted (see page 14).

In the first instance, the two particle beams for HERA were separately accelerated by a total of six pre-accelerators – both linear and ring accelerators – and progressively raised to energies of 12 billion electronvolts (gigaelectronvolts, GeV) in the case of the electrons and 40 GeV in the case of the protons. These particle beams were then fed into HERA's two accelerator rings, where they were accelerated to their final energies of 27.5 GeV in the case of the electrons and 920 GeV in the case of the protons. These particles were then circulated in the HERA rings for hours on end and brought to collision in the experimental areas, where the two beam pipes met.

Methuselah with an eventful past

The oldest link in the chain of pre-accelerators at DESY is the original "DESY" electron synchrotron – the "Deutsches Elektronen-Synchrotron". This was Hamburg's first-ever particle accelerator and gave the research centre its name.

Construction of the original synchrotron began in 1960, shortly after the research centre was founded. The challenges involved were enormous. For example, the magnets used to hold the electrons on course had to be positioned to a precision of a few tenths of a millimetre. Despite having little or no experience of building accelerators, the young DESY team was still able to construct one of the most powerful electron synchrotrons of the time. The first electrons were accelerated in the synchrotron on 25 February 1964, and the facility remained in use for research purposes until the end of 1978.

Some 300 metres in length, the DESY synchrotron was the world's largest ring accelerator when commissioned in 1964. Together with a facility in Boston, it provided by far the highest electron energies available anywhere in the world: 6 GeV. By firing these high-energy electrons at a fixed target, scientists were able to undertake a range of pioneering experiments, not least an investigation of protons with a degree of precision never before achieved. They were thereby able to show that protons do not possess a hard and clearly defined nucleus, and that if protons do actually consist of smaller constituents, the latter must be extremely small – a question that was still completely open in the early 1960s. The results of such experiments at the original synchrotron soon established DESY's name as a serious player in the world of particle physics research centres.

In 1967 researchers also began experimenting with the synchrotron radiation that the electrons emitted as they circled in the ring accelerator. They soon discovered that this intense form of light could be used to study and analyse

Bird's eye view of the DESY synchrotron

an extremely wide range of materials in much more detail than when using radiation from conventional X-ray tubes. These initial experiments with synchrotron radiation laid the foundations for what would prove to be a second and highly fruitful field of investigation at DESY: the use of accelerators as intense light sources for photon science.

Pre-accelerators at DESY

After completing its scheduled programme of experiments in 1978, the DESY synchrotron was not simply switched off. Repeatedly renovated and refurbished, it served as a pre-accelerator for the other ring accelerators in Hamburg; for DORIS from 1973 and, from 1978 onward, mainly for PETRA. In 1987, having been extensively refitted as a proton accelerator, the facility was renamed DESY III, in which capacity it then served as a pre-accelerator for HERA, in partnership with the newly built electron synchrotron DESY II. It was only with the shutdown of HERA in summer 2007 that DESY III was finally decommissioned, following 43 years of operation in various incarnations. DESY II continues to serve as an electron pre-accelerator for DORIS III and PETRA III. It is also used to generate test beams for the purpose of testing new particle detector components.

At 2.3 kilometres in circumference, PETRA II was the largest of the HERA pre-accelerators. In the course of extensive refitting from 2007 to 2009, it was modified to become one of the most brilliant X-ray sources anywhere in the world. As such, PETRA III now completes the spectrum of light sources at DESY. Other pre-accelerators currently in use at DESY are LINAC II, a 70-metre-long linear accelerator for electrons and positrons, and PIA, a 29-metre-long ring-shaped electron and positron accumulator (see page 14). LINAC III, a 32-metre-long linear accelerator in use from 1988 onward as a proton pre-accelerator for HERA, was also shut down in summer 2007. The proton source, however, is still used for test purposes.

DESY I/III

- Ring accelerator for electrons and positrons, for protons as of 1987
- Length: 317 m
- Commissioning: 1964, decommissioning: 2007
- 1964-1978: particle physics and research with synchrotron radiation
- From 1973: pre-accelerator for DORIS, PETRA and HERA (from 1987)

DESY II

- Ring accelerator for electrons and positrons
- Length: 293 m
- Commissioning: 1987
- Pre-accelerator for DORIS, PETRA, HERA and, since 2009, PETRA III

SUCCESS STORY.

DORIS III
From electron-positron storage ring to light source

DORIS was one of the world's first large storage rings. Following an initial phase in which it was used for particle physics and research with synchrotron radiation in parallel, the facility was reconfigured in 1990 into what was then Europe's brightest X-ray source. Today the storage ring serves as the reliable "work-horse" among the light sources at DESY. During its more than 35 years of operation, DORIS has paved the way for groundbreaking discoveries in the fields of both particle physics and photon science.

A new type of accelerator with a future

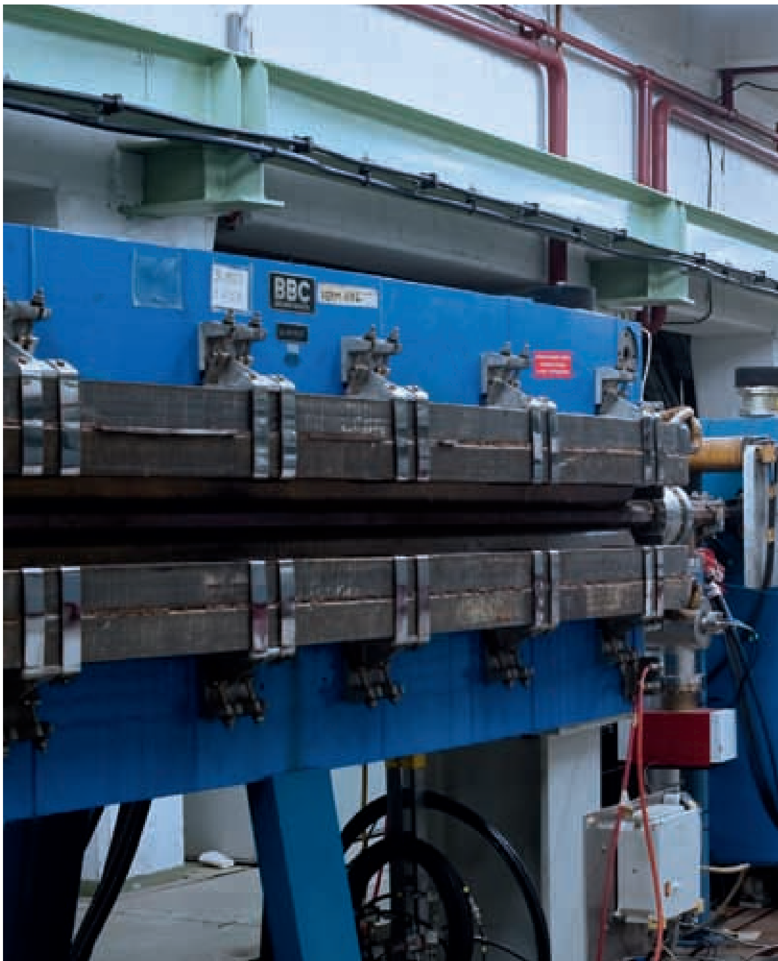
In a synchrotron the particles are only briefly accelerated before being deflected onto a stationary target. In contrast, in a storage ring two particle beams circulate at maximum energy for hours in opposite directions. They collide in flight with full force at certain locations along the ring. This makes it possible to reach substantially higher collision energies than could be achieved with a single beam and a target. This high energy makes it possible to create new particles with correspondingly higher masses, in line with Einstein's $E = mc^2$.

Storage ring technology was completely new and relatively untested in the 1960s. It was only in 1962 that the first electron-positron storage ring, which measured just a few metres in circumference, was actually built in Italy. A large storage ring with a circumference measured in hundreds of metres did not exist at that time. Whether such a machine would produce anything of scientific interest was highly uncertain. The responsible persons at DESY put their faith in such a facility nevertheless – and were soon proven right.

Heavy quarks at DORIS

Construction of the 300-metre-long storage ring DORIS (Double Ring Storage) began in 1969; the facility started up five years later. Its name stemmed from the originally two accelerator tubes, situated one above the other, in which electrons and their antiparticles, positrons, were accelerated separately. Shortly before experiments at DORIS began,

Inside the DORIS accelerator tunnel



researchers in the USA announced a spectacular discovery: they had found a new quark, the charm quark. The scientists at DORIS made decisive contributions to the particle gold rush that followed. The experiments in the USA and Hamburg delivered the final proof that protons, neutrons and similar particles are composed of yet smaller building blocks, the quarks.

After US researchers discovered the fifth quark, the bottom quark, in 1977, DORIS was reconfigured in order to study the properties of this new quark. This enabled the physicists at DORIS to come up with another sensational observation in 1987: B-mesons – particles that contain a bottom quark – can spontaneously transform into their antiparticles at a surprisingly high rate. As the then-undiscovered sixth quark, the top quark, plays an important role in this process, the results implied that the mass of the top quark must be much greater than previously expected. This was eventually proven to be the case in 1995, when the top quark was discovered at what was then the world's most powerful accelerator, the Tevatron in the USA.

Europe's brightest X-ray source

The users of synchrotron radiation also benefited from the new storage ring from the very beginning, as DORIS generated a much more stable light beam than the DESY synchrotron. It didn't take long before the original lab became too small. In response, DESY constructed HASYLAB – the Hamburg Synchrotron Radiation Laboratory – with a large experimental hall at DORIS, in order to make the radiation available on a grand scale to research groups from around the world. In 1990 and 1991 DORIS was finally extended to form what was then the brightest X-ray source in Europe. The facility received a "bulge" within which seven wigglers and undulators were installed: special magnetic structures within which the positrons emit much more intensive radiation. The reconfigured facility – DORIS III – has been serving exclusively as a source of synchrotron radiation since 1993.

Scientists have been carrying out research with synchrotron radiation at DORIS for more than 35 years. The results obtained are impressive. Again and again, the scientists and engineers have succeeded in developing new methods and instruments as well as opening up new fields of research. In many cases, what began as a local test experiment developed into a successful experimental method that established itself as a standard process in research and industry worldwide. The range of the experiments extends from effective catalysts and precision analytical methods for determining pollutants to innovative active agents for medical applications and lightweight but stable new materials.

Changing of the guard

DORIS III is now the last second-generation light source in Europe. Its fairly broad beam is excellently suited to study samples on a centimetre or millimetre scale, or entire workpieces such as those found in materials research. When it comes to smaller samples, however, researchers have to resort to third-generation sources: storage rings that were custom-built for generating light and produce radiation of a brilliance several orders of magnitude greater than second-generation sources. Experiments at these sources attain a spatial resolution better than one micrometre.

The new light source PETRA III, which was commissioned at DESY in 2009, is the world's best third-generation radiation source for hard X-rays. This also means that the DORIS era is drawing to a close. The storage ring will continue to be operated until PETRA III is running reliably in routine operation. The number of measuring stations at DORIS III will then be reduced as the focus shifts to those experimental opportunities that complement PETRA III. The long-term plan is to make the most important DORIS technologies available at PETRA III, so that DORIS III can be switched off. This will bring the 35-year success story of the first large storage ring in Hamburg to its final conclusion.

DORIS III

- Ring accelerator for electrons and positrons
- Length: 289 m
- Commissioning: 1974
- 1974-1992: particle physics and research with synchrotron radiation
- Since 1993: synchrotron radiation source
- 36 experimental stations with 45 alternately operated instruments

BRILLIANT RING.

PETRA III
A jewel with many facets

The gluon – the exchange particle of the strong force, one of nature's four fundamental interactions – was discovered in 1979 at DESY's PETRA storage ring, which in its day was the world's largest and most powerful electron accelerator. In future, the ring will be dedicated solely to generating light. In 2009 the PETRA accelerator – now in its third expansion phase – was recommissioned as the world's best storage ring-based X-ray radiation source.

Record-breaking facility PETRA

When the PETRA (Positron-Electron Tandem Ring Accelerator) storage ring was commissioned at DESY in 1978, its 2.3-kilometre-long circumference made it the largest facility of this type in the world. Even during the construction phase, the DESY designers were turning in record performances: the new storage ring was completed within less than three years – more than one year ahead of schedule – and cost a full 20 million deutschmarks less than the initially proposed budget of 100 million deutschmarks. That put DESY ahead of its competitors worldwide – the competing facility at the SLAC research centre in California was not completed until two years later.

The physicists at PETRA came up with their most important discovery in 1979, when for the first time they were able to directly observe the gluon – the exchange particle of the strong force. This force holds together the quarks – the building blocks of all matter – and is one of the four fundamental forces of nature. With that discovery DESY firmly established itself at the pinnacle of international research, and since then it has been considered to be one of the top addresses for particle research worldwide. By 1986, when the research programme at PETRA came to its end, the experiments had made a major contribution to putting today's theory of particle physics, the Standard Model, on a solid foundation.

Measuring station in the PETRA III experimental hall

The PETRA III experimental hall in a special light

It was also PETRA that provided the impulse for another important trend: the growth of the close international collaboration across political and cultural boundaries that has now become a standard feature of working life at accelerator centres around the world. The PETRA experiments were run by teams of between 50 and 100 scientists from nine countries. For the first time ever, they were responsible for constructing, operating and financing their specific detector. This model proved to be so successful that it has now been adopted worldwide, sometimes on a very large scale. Indeed, the collaborations in Geneva, which build and run the detectors at the LHC accelerator at CERN, comprise up to 3000 people from as many as 38 countries.

Conversion to a brilliant light source

Despite the completion of the scheduled programme of particle physics experiments, PETRA was not yet ready to be taken out of service. Instead, the facility was converted to PETRA II and commenced operation as a pre-accelerator in 1998 – initially for electrons and positrons, and then, from 1990 onward, also for protons for the new HERA storage ring, the largest-ever accelerator at DESY. There was something for the synchrotron radiation users, too. In 1995 PETRA II was fitted with an undulator for the purpose of generating synchrotron radiation with an intense X-ray component. From then on, PETRA II has served research with photons, providing test measuring stations for experiments with hard X-ray radiation.

In 2009 the storage ring PETRA finally celebrated its great comeback. Following the decommissioning of HERA, the DESY designers put PETRA through a further metamorphosis, leading to its rebirth after less than two years of reconstruction as PETRA III, the world's best storage ring-based X-ray radiation source. This involved comprehensive conversion and modernization work. A new 300-metre-long experimental hall was built. This stretches along one-eighth of the total circumference of the storage ring and provides 14 beamlines for up to 30 experiments.

When fabricating the floor of the experimental hall, a special technique was used. This involved casting a single one-metre-thick concrete slab to support both the accelerator and the experiments. This concrete slab, which is the world's longest monolithic cast, is mechanically decoupled from the rest of the building so that the ultra-sensitive measuring devices are not disturbed by any vibrations from the rest of the structure. The slab now carries the new components of the accelerator, which in this segment of the ring are specially optimized for synchrotron radiation production, and the undulators – some of which are as much as 20 metres in length – in which the particle beam produces the intense X-ray radiation. There was also thorough renovation of the remainder of the PETRA storage ring, the tunnel being almost completely stripped and then refitted.

What particularly distinguishes this new light source at DESY is the presence of a number of specially designed undulators which produce X-ray radiation of an exceptionally high brilliance. In simple terms, this means that a very large number of photons (light particles) are collimated within a very small area to form an extremely intense beam of X-ray light. In fact, PETRA III delivers a photon flux over an area of a single square millimetre that is as high as DORIS III presently produces over several square centimetres. This provides users from throughout the world with excellent research opportunities. A whole range of experiments ranging

Bird's eye view of the PETRA III experimental hall (left)

from the investigation of new materials to molecular biology and medicine will be possible at 30 experimental stations. Users from German and international research institutions and industrial researchers and developers – in particular, those investigating very small samples or requiring extremely tightly collimated and very short-wavelength X-rays for their analyses – will benefit from this new light source.

A storage ring with exceptional properties

As the world's leading storage ring-based X-ray radiation source, PETRA III provides a new benchmark among third-generation light sources. The quality of a synchrotron radiation source is determined mainly by the emittance of the particle beam, which is defined as the product of the beam area and divergence. The lower the emittance, the better the collimation of the beam, and the greater the brilliance of the synchrotron light that can be generated with it. Thanks to the installation of 20 damping wigglers in the northern and western sections of the ring, PETRA III has a horizontal emittance three to four times lower than similar high-energy storage rings and is therefore the most brilliant radiation source of its type in the world. As the stored particles pass through these four-metre-long magnetic structures, they emit radiation, which damps – i.e. reduces – their movement in the horizontal plane, thus enhancing beam collimation and thereby ensuring that the light beams generated are more focused and more brilliant.

PETRA III also uses a special mode of operation that offers scientific users optimal experimental conditions. In the majority of storage ring-based light sources, a particle beam comprising a determinate number of particle bunches is injected into the accelerator ring. This beam then circulates for several hours, generating synchrotron radiation as it passes through the bending magnets, wigglers and undulators. In the process, it gradually loses intensity until the beam current is so low that no more suitable radiation can be generated. At this point, the particle beam is diverted from the accelerator to a special beam dump, where it is absorbed. A new particle beam is then injected into the ring, and the process recommences.

The beam pipe between the magnets of a PETRA III undulator

By contrast, PETRA III is operated in so-called top-up mode. This means that the particle current in the storage ring is kept constant to a variability of just one per cent by frequent injections of fresh particles which are “hitched” to the existing particle bunches. Scientific users greatly benefit from this mode of operation, since it enables them to conduct their measurements under uniform conditions rather than having to allow for ever-changing radiation intensity. Since the intervals between top-up injections can be as short as 70 seconds when running with a 40-bunch filling pattern in the storage ring, both the injector and the pre-accelerator systems must operate extremely reliably. These were therefore thoroughly overhauled in the course of the work to convert and modernize PETRA so as be able to guarantee the requisite high reliability.

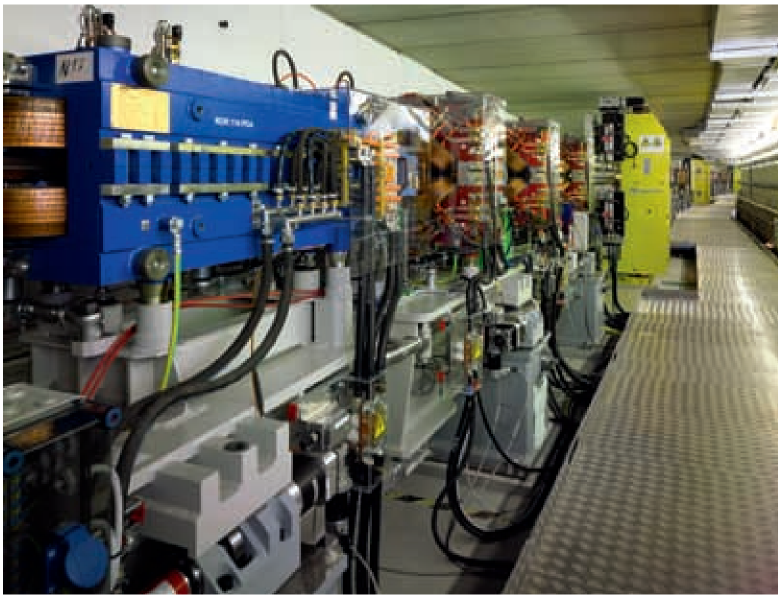
All systems go for PETRA III

In fact, the work to convert the PETRA accelerator into the world’s most modern third-generation synchrotron radiation source was so extensive that it almost amounted to a complete rebuild. It was therefore all the more gratifying that the project could be finished on time and to budget, and that this highly complex facility was commissioned with practically no teething troubles whatsoever. It was back in December 2008 that the PETRA team began the job of testing all the systems in the tunnel. The 700 or so magnets responsible for guiding, bending and focusing the particle beam were switched on for the first time sector by sector, checked for the correct polarity and for short circuits, and tested under normal operating conditions; the vacuum pumps were tested, as were the various control and safety systems; and the radio-frequency system was checked along with the water cooling system and the temperature and pressure sensors.

In mid-April 2009, the almost two-year project to convert PETRA was finally completed. On Easter Monday, particles circled the PETRA ring for the first time since June 2007. Initially they only completed a few laps, but before long they were circling the accelerator ring on the calculated path for minutes on end, at a rate of 130 000 times per second. The trickiest section for the commissioning process was the 300 metres in the new experimental hall, where the undulators’ magnetic structures for producing synchrotron radiation have to be positioned very close to the particle beam. The beam pipe in the hall therefore has a number of bottlenecks measuring just a few millimetres in height, through which the beam must pass.

Like test pilots, the accelerator team thoroughly explored the limits of the new facility. For example, how much beam deviation can be tolerated in the vacuum tube without “scratching” the wall? And how do particles react to different control signals from the control room? At the same time, running the particle beam also provided an opportunity to improve the vacuum in the accelerator. This is because the synchrotron light emitted by the positrons detaches remaining gas molecules from the walls of the vacuum chamber. As a result, these molecules are more effectively extracted by the vacuum pumps, thus further reducing the pressure in the beam pipe.

In mid-July 2009 the two magnetic halves of the undulators already in place were moved close together, with the result that the positrons in the particle beam were made to follow a slalom path. PETRA III generated its first X-ray radiation! In parallel with the process of further optimizing the accelerator operation and light generation, work is continuing in the experimental hall to install the 14 beamlines where the scientists will set up their measuring stations. Initial test experiments with X-ray light from PETRA III took place in autumn 2009, and regular experiment operation of the most modern third-generation synchrotron radiation source is scheduled to commence in 2010 with users from around the world.



The PETRA III storage ring within the experimental hall, with bending magnets (blue), focusing magnets (red) and undulators (yellow)

PETRA III

- Ring accelerator for electrons and positrons, subsequently also for protons
- Length: 2304 m
- Commissioning: 1978
- 1978-1986: particle physics
- 1987-2007: pre-accelerator for HERA and source of X-ray radiation
- Since 2009: world’s most brilliant storage ring-based X-ray radiation source
- 14 experimental stations with up to 30 instruments

POINTING THE WAY.

HERA
The super electron microscope

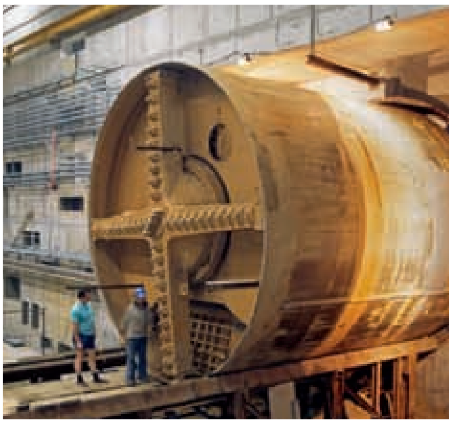
The Hadron-Electron Ring Accelerator HERA was the largest particle accelerator at DESY and Germany's largest research instrument. The 6.3-kilometre-long super electron microscope provided physicists with the world's clearest view of the proton's interior. Although operation of the facility ended in summer 2007, the evaluation of the data continues. The experience gained during the construction and operation of HERA is also finding its way into new accelerator projects.

An ambitious plan

As DESY's physicists planned the future following the construction of PETRA, one thing was certain: the next project would have to be unique and open the door to revolutionary new ways of studying the microcosm. Because the other accelerator centres were operating with particles and their antiparticles, the decision-makers at DESY opted to build a "super electron microscope" for protons – a machine that would provide insights into the innermost structure of matter.

The proposal for the Hadron-Electron Ring Accelerator HERA was drawn up at the start of the 1980s. It was to be the world's only storage ring in which two different types of particle would collide head-on. The particles involved would be the light, point-like electrons and hydrogen nuclei – in other words, protons, which are members of the hadron family and are almost 2000 times heavier than electrons. In such collisions the electron acts as a miniscule probe that scans the interior of the proton. The higher the energy of the particle collision, the deeper physicists are able to gaze into the proton, and the more details are revealed.

However, accomplishing this feat requires two different, technically very demanding accelerators. Whereas particles and antiparticles, which differ mainly in that they have opposite charges, can be stored simultaneously in the same ring accelerator, two types of particle as different



as electrons and protons have to be accelerated in two separate rings before being brought to collision at the highest energies using an extremely sophisticated beam guidance system. No one had ever attempted to build such a facility before. Nonetheless, the plan succeeded. Approval for the construction of HERA was granted in April 1984. In November 1990 DESY celebrated the symbolic start-up. Despite the enormous technical challenges, HERA was completed within the specified schedule and budget.

Pioneering work for HERA

Sizeable challenges were involved in the construction of the proton ring for HERA. For example, at HERA's high energies, extremely powerful magnetic fields are necessary to make the heavy protons follow the curve of the accelerator ring. Indeed, it requires magnetic fields around three times as strong as those that can be reached by conventional magnets with iron yokes and copper coils. The only feasible way of generating such field strengths is to use superconductivity – the ability of certain materials to conduct electricity without loss at exceedingly low temperatures. For DESY, this was an adventure into new technological territory. At the time of planning, the world's only other large superconducting accelerator, the Tevatron proton-antiproton storage ring at Fermilab in Chicago, was still under construction. There, the physicists and engineers were battling to overcome their own problems with the magnet technology. As a consequence, DESY had to develop the proton accelerator technology for HERA more or less from scratch.

The design developed by DESY for the 650 superconducting magnets of the HERA proton ring was an immediate success. Indeed, it has since been adopted worldwide. For example, the magnets for the world's most powerful accelerator, the Large Hadron Collider LHC in Geneva, also incorporate major elements of the HERA design. As for European industry, HERA offered a unique opportunity, since it was the first-ever project of this type in which all the magnets were to be manufactured by the private sector. By the same token, it was also a golden opportunity for companies to gain experience of superconducting technology and cryogenics on an industrial scale.

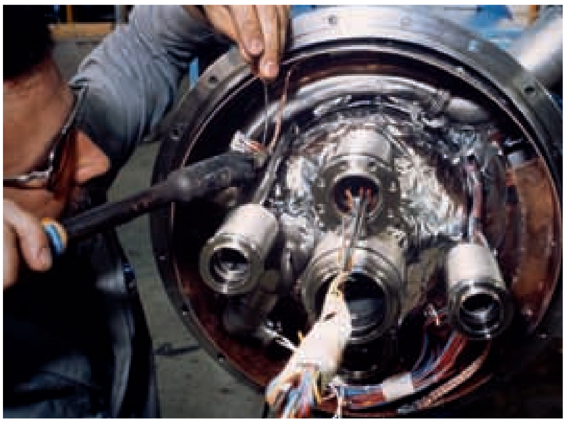
Europe's largest refrigerator...

One of the biggest challenges involved in the construction of superconducting magnets is to provide the requisite cooling. In order to chill the magnet coils to the required operating temperature of minus 269 degrees Celsius (one degree warmer than outer space!) over the entire 6.3 kilometres of the HERA ring, DESY built what was in 1986 the largest refrigeration plant in Europe. Installed in a building 2500 square metres in area, this operated in principle like a refrigerator or the refrigeration unit of an air conditioner, the only difference being that it used helium as a refrigerant. The gas was first of all compressed and purified before being expanded, cooled and liquefied in a system of heat exchangers and turbines. The liquid helium was then pumped into the HERA ring, where it flowed through the superconducting magnets in order to cool them.

... serving FLASH and the European XFEL

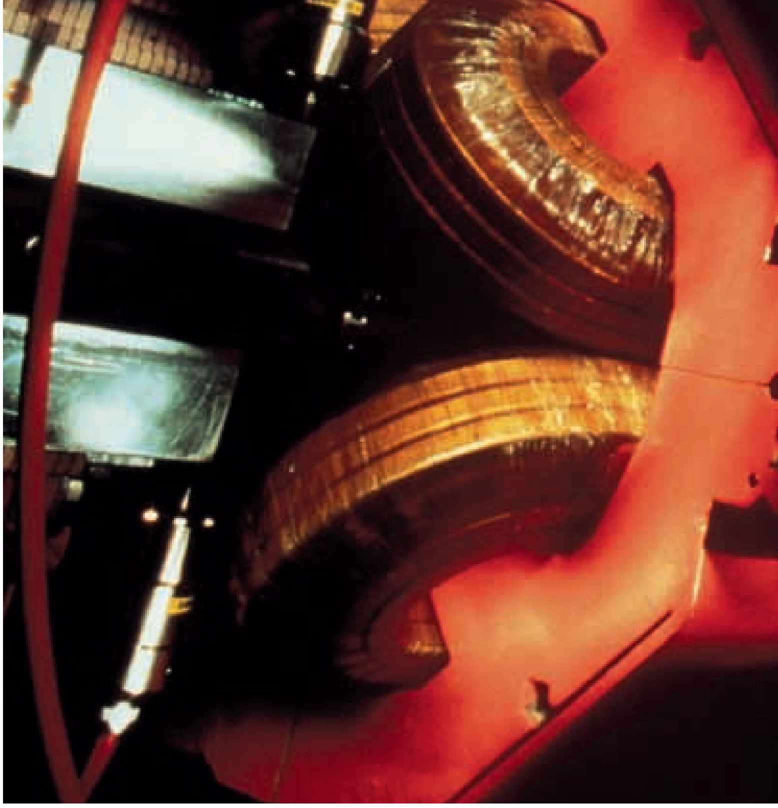
Although HERA ceased operation in summer 2007, the department of Cryogenics and Superconductivity – one of the largest groups at DESY's Accelerator Division – still has plenty of work on its hands. Here too the wealth of experience at DESY has been put to immediate use for new projects, not least the development of the superconducting accelerator technology for the free-electron lasers FLASH and European XFEL, and the projected International Linear Collider ILC (see page 48).

One of the three lines of the former HERA refrigerating plant has already been producing liquid helium for the linear accelerator of the free-electron laser FLASH for a number of years now. The helium is used to chill the seven 12-metre-long superconducting accelerator modules, which boost the electrons to high energies, to their operating temperature of minus 271 degrees Celsius. The other two refrigeration lines will be used to provide liquid helium for the 1.7-kilometre-long linear accelerator of the X-ray laser European XFEL, which is based on the same accelerator technology as FLASH and is scheduled to go into operation in 2014. Here around 100 superconducting accelerator modules will have to be reliably cooled to a temperature of minus 271 degrees Celsius – a major challenge, even for the seasoned experts at DESY.



RACE COURSE

HERA in operation



In the case of HERA, two different kinds of particle were accelerated in separate rings and then made to collide by means of a sophisticated system of magnets. This meant it was a uniquely challenging facility to operate. For facilities that collide particles and their antiparticles, the two particle beams can be circulated in one single beam pipe. Since the particles and antiparticles only differ in terms of their electric charge, they both feel the same forces and therefore automatically arrive at the same place in the ring at the same moment. HERA, however, with its two 6.3-kilometre-long accelerators and over 800 bending magnets, 1340 focusing magnets, 1200 power supply units and 1500 vacuum pumps, required a series of painstaking adjustments before it was operating smoothly.

Furthermore, at that time HERA was the only accelerator facility at which multiple experiments of different types were operated in parallel. These were the two collision experiments H1 and ZEUS and the two beam-target experiments HERMES and HERA-B, in which only one of the particle beams is fired at a fixed target. Unlike accelerator facilities fitted with same types of detector, HERA therefore had to be operated in line with the fundamentally different requirements of each experiment.

Ultra-thin particle beams

A particle beam is not a continuous stream of particles but rather lots of individual bunches comprising billions of particles. It is the job of the person in the control room to ensure that these bunches do not disperse, that they follow their prescribed path around the curve of the accelerator ring, that they are not disturbed by any collisions with residual gas molecules in the vacuum tube, that individual electron and proton bunches arrive at the interaction points at the same time, and that, once there, the electron and proton beams collide with one another with an accuracy of a fraction of a millimetre.

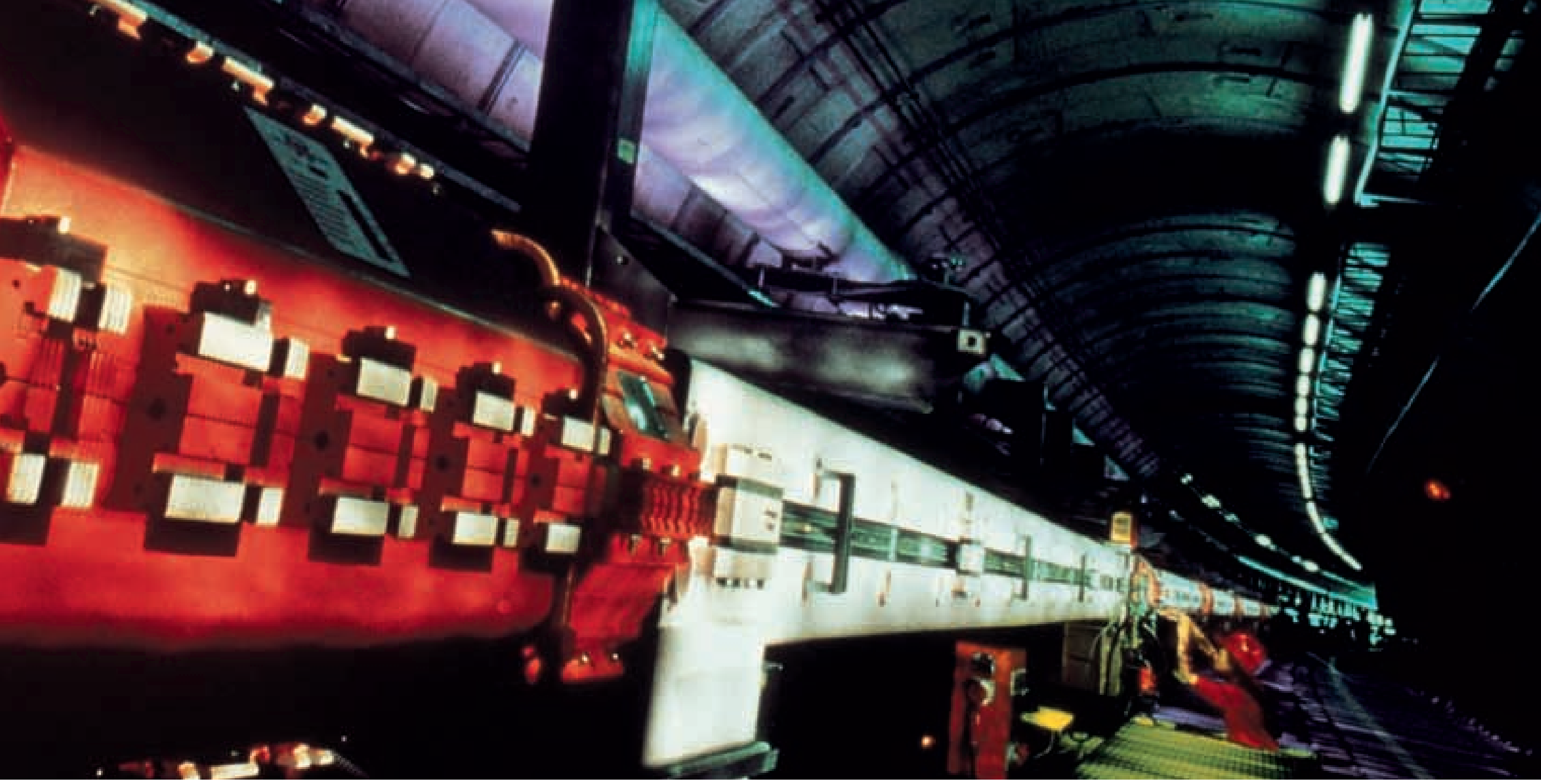
As an indication of the complexity of this task, it should be recalled that the particle beams at the collision points are only about as thick as a single human hair. It can therefore take several years before a facility as technically demanding as HERA is operating in such a way that it consistently provides the optimal conditions required for the various experiments at the push of a button.

Fine-tuning for increased performance

HERA was in operation for research purposes from 1992 to 2007. Over this time, its performance and efficiency were continuously increased. Indeed, with regard to certain parameters – such as the luminosity, i.e. the number of particle collisions the facility provides – HERA even surpassed the design values.

In order to learn how to handle proton energies as high as 820 billion electronvolts (gigaelectronvolts, GeV), the HERA team initially operated the facility with particle beams of lower intensity and at lower luminosity, and then progressively reduced the cross-section of the particle beams while filling the ring with more and more particle bunches. In 1997 the integrated luminosity over one measuring period exceeded the design value for the first time. In 1999, HERA achieved the same luminosity for electrons as had been recorded for positrons in 1997. This was accomplished even though the proton energy had been increased from 820 to 920 GeV in the meantime, and without problems despite the increased load on the components.

The year 2000 marked a highly successful period of operation, with HERA delivering more collisions than in any other year before. A comprehensive programme of work then began in autumn of that year to modify the accelerator and the detectors, with the aim of achieving a fourfold increase in HERA's luminosity and providing both collision experiments with polarized electrons. All in all, almost 80 magnets were redesigned and installed and the two interaction zones were extensively modified. Following this luminosity upgrade, restarting HERA proved to be much more difficult than was initially anticipated, not least because the facility had become



what was essentially a new accelerator with all the normal teething troubles that this involves. However, with the support of both external and internal advisory bodies, teams from HERA and the individual experiments were able to identify and resolve the problems one by one, with the result that by the start of 2004 the two collision experiments were recording data at the planned beam currents.

Flying high with HERA

From then on, it was full steam ahead. The HERA team concentrated on continually increasing the beam currents, while the experiment teams worked on improving the efficiency of the data taking with their detectors. At the start of its 2004 summer shutdown, HERA had exceeded the maximum luminosity achieved during the first operating phase and become the first storage ring worldwide to provide longitudinally polarized high-energy positrons for use in collisions. In 2005 the specific luminosity significantly exceeded the design value. Thanks to its untiring optimization work, the HERA team was able to improve the facility's availability, peak luminosity and background conditions year after year and thus ensure ideal measuring conditions at highest luminosity for the HERA experiments.

HERA's operation, which had begun with the first particle collisions on 19 October 1991, came to an end at 23:30 on 30 June 2007. But the "HERA adventure" is by no means over. Evaluating the comprehensive mass of data that the HERA experiments have recorded over the course of 16 years of operation will continue to occupy particle physicists for quite some time. Many of the insights gained with HERA have already been included in textbooks and form part of our fundamental knowledge of how our world is put together. The evaluation of the remaining measurement data will continue to provide unique insights into the inner structure of the proton and the nature of the fundamental forces for many years. The HERA physicists will thus ultimately be able to present a comprehensive picture of the proton that is unprecedented in terms of its precision and multifaceted quality. Given the unique status HERA enjoys, this picture will remain valid and unchallenged for years and possibly decades to come.

The large HERA detectors have meanwhile been dismantled, but the accelerator itself is still being maintained. There are various ideas for its future use – and should one of them be implemented, it will be possible to bring HERA back to life without too much difficultly.

HERA

- Electron-proton storage ring for particle physics
- Length: 6336 m
- Research operation: 1992 to 2007
- Evaluation of the data continues
- Experiments: H1, ZEUS, HERMES, HERA-B

FRONT RUNNER.

FLASH
World record laser flashes

Since 2005 researchers at DESY have had access to a unique new type of light source: FLASH, the world's only free-electron laser to generate radiation in the vacuum ultraviolet and soft X-ray regions. This is a pioneering facility in a number of ways. As the world's first-ever X-ray free-electron laser with a superconducting linear accelerator, FLASH is a source of indispensable knowledge for the development of future accelerators and X-ray lasers. At the same time, it provides researchers from virtually all the natural sciences with unprecedented experimental possibilities.

Unique pioneering facility

At the start of the 1990s, DESY's accelerator constructors and international partners first began work on a concept called TESLA to develop a new linear accelerator for particle physics (see page 48). As the accelerator was to be fitted with superconducting modules, it was decided to build a 100-metre-long test facility at DESY – the TESLA Test Facility TTF – in order to investigate this highly challenging technology under realistic conditions. By successfully implementing and testing all the main components required for a superconducting electron-positron linear accelerator, the team delivered conclusive proof of the technical feasibility of this type of facility. Similarly, the TTF also yielded the world's first-ever demonstration of the viability of the concept of a powerful X-ray laser, when at the beginning of 2000, following its conversion into a free-electron laser, the test facility first produced laser light with a wavelength of less than 100 nanometres.

The TTF had thus admirably fulfilled its pioneering task during the initial operating phase. In 2003, it was then extended to a length of 260 metres and converted to a free-electron laser in the soft X-ray range for use in photon science at DESY. To mark the official start of user operation in 2005, it was renamed FLASH (Free-Electron Laser in Hamburg). Since then, researchers at DESY have had access to a unique light source – the world's first free-electron laser with wavelengths extending into the soft X-ray region.

Record laser in the X-ray region

For many years there was fierce competition between constructors of radiation sources around the world to see who would be the first to develop a high-power laser in the X-ray region. During this period the international FLASH team set one record after another, progressively reducing the wavelength of the laser radiation until the target of 6.5 nanometres was finally achieved in 2007.

This remained unsurpassed for two years, until the start-up of the Linac Coherent Light Source LCLS in California. This free-electron laser produces radiation of an even shorter wavelength – in the region of 0.15 nanometres, which is in the hard X-ray range. Nevertheless, FLASH remains unique as the world's only free-electron laser to generate high-power ultra-short pulses of laser light in the vacuum ultraviolet and soft X-ray ranges.

As such, FLASH outperforms not only the world's best synchrotron radiation sources but also the very latest conventional X-ray lasers. For while it is true that synchrotron radiation sources also produce tightly collimated radiation, FLASH is delivering X-ray radiation with genuine laser properties – i.e. as a perfectly collimated beam. Similarly, FLASH has a peak brilliance several orders of magnitude greater than the beams produced by conventional lasers in the X-ray range – higher even than that of the most advanced synchrotron radiation sources. Furthermore, the laser light at FLASH is generated in ultra-short pulses, thus providing researchers with unique experimental possibilities.

Revolutionary experimental possibilities

FLASH consists of a linear accelerator some 150 metres in length, comprising sequentially connected superconducting accelerator modules which boost the electrons to an energy of one billion electronvolts (gigaelectronvolts, GeV). The electron beam then passes through a 30-metre-long periodic array of magnets known as an undulator, which forces the particles to follow a rapid slalom course. In accordance with the principle of self-amplified spontaneous emission (SASE), the particles emit pulses of radiation that reinforce one another to form short-wavelength, high-intensity flashes of laser light. These are then led into the FLASH experimental hall, and distributed to a total of five experimental stations that are available to international research groups. In the medium term DESY is planning, in close collaboration with the Helmholtz Zentrum Berlin, to enlarge FLASH by constructing a second undulator line in a separate tunnel with a second experimental hall capable of accommodating an additional six experimental stations (FLASH II).

User time at FLASH is in great demand. In fact, just one year after the start of user operation the facility was already overbooked by a factor of three. As early as the first measuring period, results had already begun to substantiate the high hopes that researchers had placed in the revolutionary new experimental capabilities of the free-electron laser. Such experiments ranged from the generation and examination of plasmas and the study of gases and clusters to preliminary investigations of experimental methods for complex biomolecules – methods of the type also intended for use at the X-ray laser European XFEL. A number of groups successfully used the ultra-short light pulses from FLASH in order to observe, on extremely short time scales, rapid processes as they actually unfold – much as in a slow-motion film. The use of short-wavelength radiation to investigate such processes ranks among the most important new applications of this type of X-ray laser.

Pioneer for X-ray lasers and linear accelerators

Yet FLASH is not only in big demand as a new research instrument. In addition, it continues to play an important pioneering role both for the X-ray laser European XFEL, which is now under construction in the Hamburg region and will generate radiation of a wavelength as short as one-tenth of a nanometre, and for the International Linear Collider ILC, the next major accelerator project in the world of particle physics. The linear accelerators for FLASH, the European XFEL and the ILC are all based on the superconducting TESLA accelerator technology. FLASH thus offers an ideal platform for developing all the requisite components to the series-production stage.

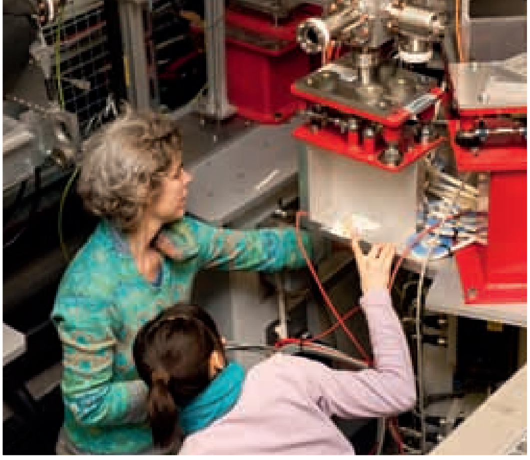
At the same time, the scientists, engineers and technicians working on FLASH are also involved in developing and testing further elements for the European XFEL such as the undulators – the arrays of magnets responsible for generating the X-ray flashes –, the optical components, measuring devices and detector systems. By the same token, operating FLASH also provides valuable experience with the processing of large volumes of data. And, last but not least, FLASH offers researchers an opportunity to explore new experimental methods for use with future X-ray lasers. Participation in the FLASH project is also of major long-term interest to industrial companies, since the technical know-how thus acquired will qualify them to take part in the construction of the European XFEL and other linear accelerators around the world.

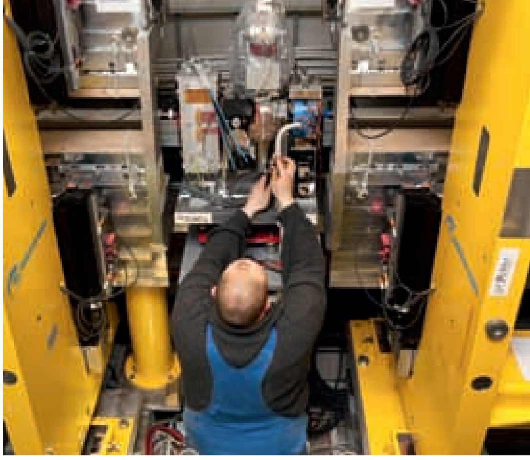
Pushing back technical frontiers

In the period since 2005, FLASH has served as a reliable source of laser light for research groups from around the world. At the same time, the FLASH team has continued to investigate ways of enhancing the facility. In the process, they have repeatedly pushed back the frontiers of what is technically feasible. For one of the features of key technologies such as the free-electron lasers is their rapid development, and their design engineers are thus continuously confronted with the challenges of the near and more distant future.

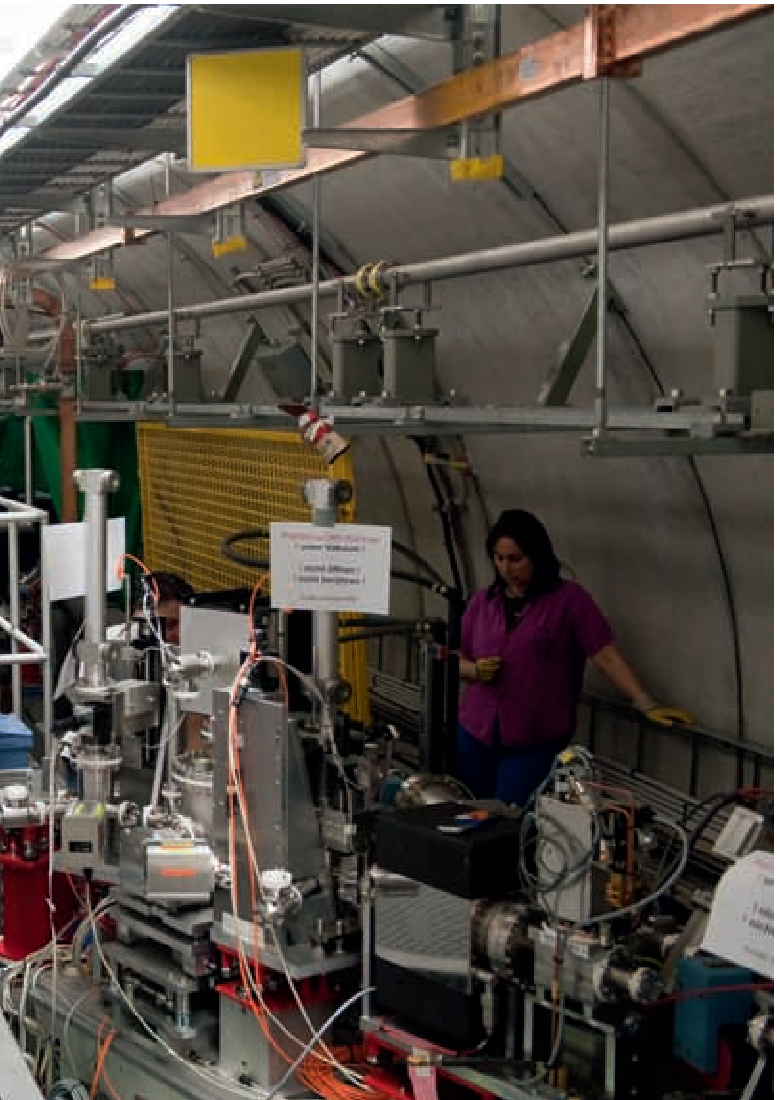
In September 2009 an extensive programme of work was started to upgrade large parts of the accelerator. In particular, the electron source – the so-called photo injector – has been replaced with a new electron source developed at PITZ, DESY's Photo Injector Test Facility in Zeuthen. This photo injector generates considerably less dark current – a source of interference – and also better-ordered particle bunches (see page 44), both of which substantially enhance the quality of the laser light.

In addition, a further accelerator module has been added to the six already installed, with the aim of increasing the beam energy from 1 to 1.2 GeV. Thus equipped, FLASH





will be capable of producing laser light with wavelengths of less than five nanometres. Another major aspect of the upgrade was the installation of an accelerator module built at the Fermilab research centre in Chicago, which comprises four superconducting cavities operating at a frequency of 3.9 gigahertz (GHz) rather than the 1.3 GHz customary at FLASH. This makes it possible to shape the form and length of the laser flashes, thus providing research teams with exactly the type of radiation they require for their experiments. The installation of this accelerator module also constitutes an important test for the forthcoming X-ray laser European XFEL, since it is to be equipped with similar modules.



Working in cooperation with the University of Hamburg, the FLASH team has also installed the so-called seeding experiment sFLASH in a 40-metre section of the tunnel. At present, the light amplification in FLASH is triggered by the flashes of radiation the particle bunches emit on their way along the undulator. When seeding is employed, however, the amplification process is started using the light from a conventional laser with a wavelength corresponding to that of the FLASH radiation. As a result, it will be possible to significantly reduce the fluctuations in intensity that previously occurred between individual flashes and also further enhance the laser properties of the radiation.

The FLASH team will be looking initially to demonstrate the feasibility of seeding at a wavelength of 30 nanometres and then progressing to shorter wavelengths. The radiation thus generated is to be made available to researchers at a separate beamline, without interference to the rest of FLASH operations. At the end of this comprehensive five-month upgrade, users will therefore have access to an enhanced FLASH facility that, true to its pioneering role, will continue to offer a host of new and unique experimental possibilities.

The FLASH tunnel during the upgrade work

FLASH

- Free-electron laser with superconducting linear accelerator
- Length: 260 m
- 1992-2005: test facility for superconducting accelerator technology and FEL technology
- Since 2005: FEL facility for photon science
- Produces extremely brilliant laser radiation with wavelengths of between 5 and 60 nanometres using the SASE principle
- Five experimental stations

LIGHT HOUSE.

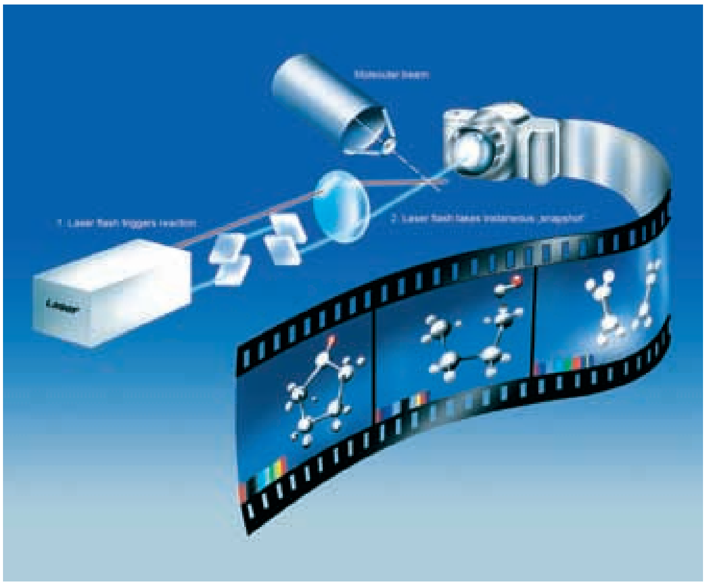
European XFEL
Europe's beacon for science

The free-electron X-ray laser European XFEL currently taking shape in the Hamburg metropolitan area is an absolute highlight in the genuine sense of the word. The laser is being built as a European project in which DESY is participating to a substantial degree. It is scheduled to go into operation in 2014. As the only light source of this type in Europe, the European XFEL will deliver high-intensity, ultra-short flashes of laser light in the hard X-ray region. It therefore promises to open up a whole new realm of research opportunities for scientific and industrial users worldwide.

X-ray laser in the Hamburg region

Like its "little brother" FLASH, which has been in operation at DESY since 2005, the European XFEL X-ray laser owes its existence to the development work carried out in relation to the superconducting TESLA accelerator technology. These development activities were initiated by DESY and its international partners at the start of the 1990s (see page 48). Back then it became clear that the TESLA technology is ideally suited to driving a free-electron laser in the X-ray region. At the beginning of 2003 the German research ministry approved the construction of such an X-ray laser in principle as an independent European institution. Since then, scientists have been working on the realization of the facility, which is officially known as the European XFEL, in Hamburg and Schleswig-Holstein. DESY is a key project partner.

Construction commenced in January 2009. The 3.4-kilometre-long facility extends from the DESY site in Hamburg to the Schleswig-Holstein town of Schenefeld, where a research campus is under construction. It will accommodate an experimental hall with space for ten measuring stations. The European XFEL is being constructed and will be operated by the European XFEL GmbH, an independent non-profit company of limited liability under German law. Twelve countries are currently participating in the project, with China planning to join. As Germany's representative, DESY is responsible in particular for coordinating the international consortium of 17 institutes that is constructing the accelerator complex for the facility. The start of commissioning is scheduled for 2014.



Ultra-fast lasers such as the European XFEL can be used to film chemical reactions.

Revolution in X-ray research

The development of lasers in the infrared and visible regions has triggered a real revolution in science and technology over the past 40 years. Today, lasers are an essential element of everyday life, to be found in a whole variety of applications such as data storage, printing technology and distance measurement as well as products such as cutting and welding tools, laser pointers and laser scalpels. Similarly, since the 1960s the use of the synchrotron radiation produced by ring accelerators in both the ultraviolet and the soft and hard X-ray regions has led to great experimental advances and discoveries in nearly all the natural sciences. With the construction of powerful X-ray lasers such as the European XFEL, natural scientists of all disciplines are now hoping to extend the success story of the laser into the X-ray region – and, at the same time, to revolutionize research with X-rays.

The X-ray radiation produced by free-electron lasers displays substantially better properties than synchrotron radiation. It is not only many times more brilliant than synchrotron radiation but is also coherent – i.e. laser-like – and emitted in pulses shorter than 100 femtoseconds (quadrillionths of a second) and has a peak power of several gigawatts. This will create the kind of research opportunities of which scientists could so far only dream. With the X-ray flashes generated by the European XFEL, scientists will be able to decode the atomic details of viruses and cells, capture three-dimensional images of the nanoworld, film chemical reactions and study processes under the kind of extreme conditions that prevail, for example, in the interior of planets. Such research will provide new insights into practically all of the scientific and technical fields that are of central importance to our everyday lives, including medicine, pharmacology, chemistry, materials science, nanotechnology, power engineering and electronics.

European XFEL and FLASH

The 3.4-kilometre-long European XFEL utilizes the same principle and technology as the FLASH free-electron laser at DESY, albeit on a much larger scale. Whereas the 150-metre-long linear accelerator of FLASH boosts the electrons to an energy of 1.2 billion electronvolts (1.2 GeV), the 1.7-kilometre-long accelerator of the European XFEL reaches particle energies of 17.5 GeV. The electrons then pass through undulators – long magnetic structures – which induce them to emit extremely intense pulses of laser light. These are then led into an experimental hall and distributed to the various measuring stations, where scientists from around the world conduct their research with the laser light.

One of the major differences between the two facilities lies in the wavelength of the radiation they generate. The shortest wavelengths possible with FLASH are around five nanometres, which lies within the soft X-ray range. By comparison, the European XFEL will generate radiation of a wavelength more than 50 times shorter – in the hard X-ray range. It will therefore be suitable for imaging even smaller structures than is possible with FLASH. Using the light from FLASH, scientists can already discern individual molecules. With the European XFEL, however, they will be able to observe the atomic structure of those molecules.

The international perspective

In addition to the European XFEL, there are two other free-electron lasers in the hard X-ray range: LCLS went into operation in California in 2009, SCSS is currently under construction in Japan. All three facilities function in a similar manner, but with the difference that both LCLS and SCSS employ normally conducting accelerator technology – unlike the linear accelerators of the European XFEL and FLASH, which use superconducting technology operating at a temperature of minus 271 degrees Celsius. The use of the TESLA accelerator technology has decisive advantages.

In particular, the use of superconducting accelerator modules enables the generation of an exceptionally high-quality electron beam composed of many electron bunches aligned one behind the other. This means that the European XFEL will be able to generate many more light flashes per second than the other two facilities. Whereas LCLS and SCSS are able to deliver 120 and 60 light flashes per second, respectively, the European XFEL will be capable of 27 000 flashes per second. As a result, certain experiments will only be possible at the European XFEL, others can be conducted much more quickly. Similarly, the greater number of electron bunches will also allow for more experimental stations to be operated simultaneously.

Although the European XFEL will commence research operation later than the two other facilities, this does mean that the European team will benefit from the experience gained in Japan and the USA. At the same time, the excellent technical and scientific infrastructure and the fact that the European XFEL will provide specially developed measuring instruments will both ensure optimum conditions for research. Last but not least, the experience gained by DESY and its partners from abroad with the pioneering FLASH facility will be of direct benefit for the construction and operation of the European XFEL.

European XFEL

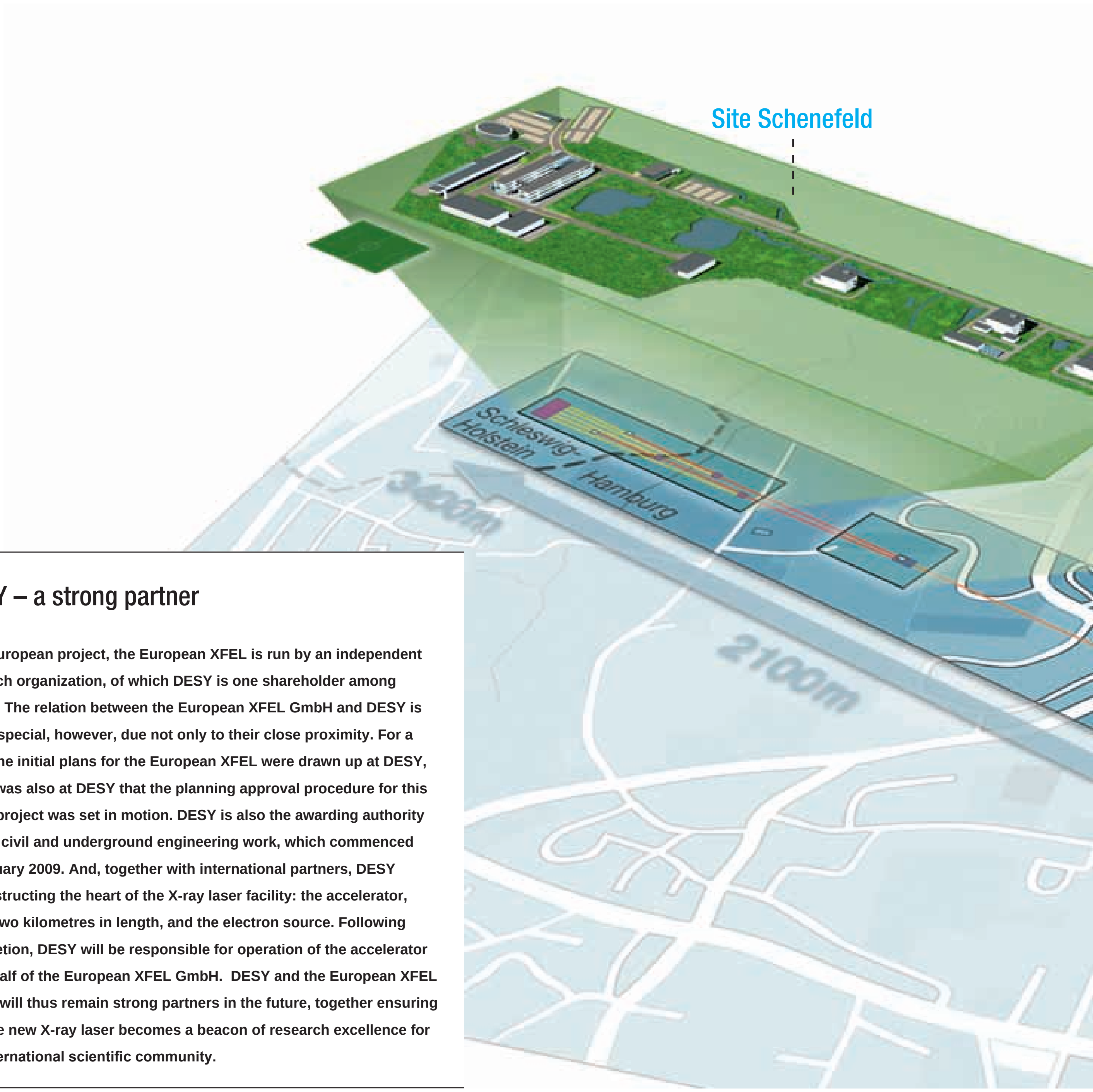
- European project with substantial DESY involvement
- Construction and operation: European XFEL GmbH (non-profit)
- Free-electron laser with superconducting linear accelerator
- Length: approx. 3.4 km
- Produces extremely brilliant laser radiation with wavelengths of between 0.1 and 6 nanometres using the SASE principle
- Under construction; start of commissioning: 2014
- An underground experimental hall with space for ten measuring stations
- Scope for constructing a second experimental complex

The X-ray laser European XFEL

The Hamburg area will soon boast a research facility of superlatives: the European XFEL will generate ultrashort X-ray flashes – 27 000 times per second and with a brilliance that is a billion times higher than that of the best conventional X-ray radiation sources. Thanks to its outstanding characteristics, which are unique worldwide, the facility will open up completely new research opportunities for scientists and industrial users.

The European XFEL will be located mainly in underground tunnels, which can be accessed on three different sites. The 3.4-kilometre-long facility will run from DESY in Hamburg to the town of Schenefeld (Schleswig-Holstein). The Schenefeld site will host the research campus on which, starting in 2015, international teams of scientists will carry out experiments with the X-ray flashes.

To generate the X-ray flashes, electrons will first be accelerated in a 1.7-kilometer-long superconducting linear accelerator and then directed through special arrangements of magnets (undulators), which force them on a slalom course. In the process, the particles emit radiation that is increasingly amplified until an extremely short and intense X-ray flash is finally created.



DESY – a strong partner

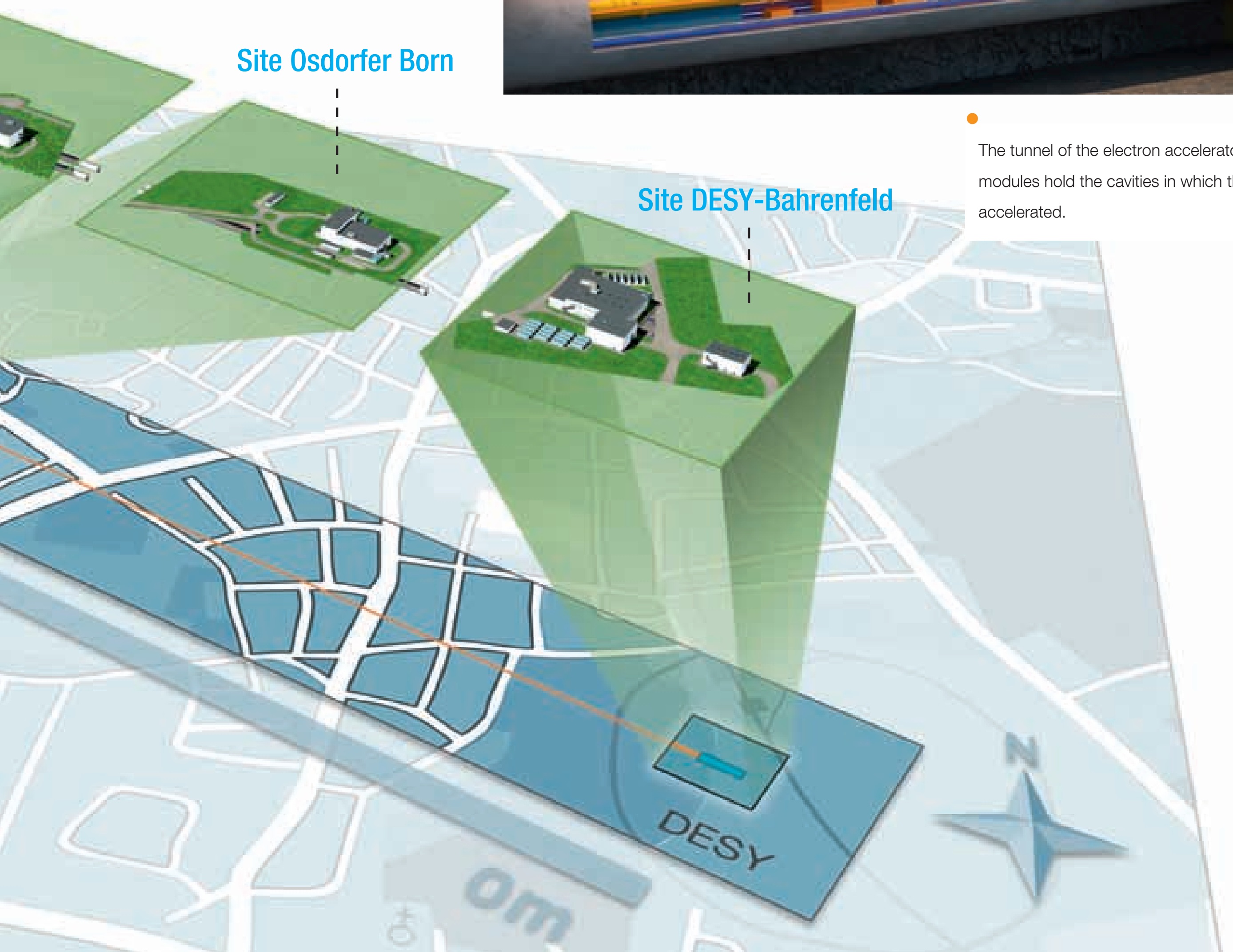
As a European project, the European XFEL is run by an independent research organization, of which DESY is one shareholder among others. The relation between the European XFEL GmbH and DESY is rather special, however, due not only to their close proximity. For a start, the initial plans for the European XFEL were drawn up at DESY, and it was also at DESY that the planning approval procedure for this major project was set in motion. DESY is also the awarding authority for the civil and underground engineering work, which commenced in January 2009. And, together with international partners, DESY is constructing the heart of the X-ray laser facility: the accelerator, some two kilometres in length, and the electron source. Following completion, DESY will be responsible for operation of the accelerator on behalf of the European XFEL GmbH. DESY and the European XFEL GmbH will thus remain strong partners in the future, together ensuring that the new X-ray laser becomes a beacon of research excellence for the international scientific community.

The central building on the research site in Schenefeld. The tunnels from which the X-ray flashes are led to the experimental stations will end in the underground hall beneath the main building. This will house labs and offices, seminar rooms, an auditorium and a specialist library.

Beneath the switchyard hall on the site Osdorfer Born the accelerated electrons will be distributed to the various tunnels for the first time. In addition, all the electrons that cannot be used any further will be stopped here in special beam dumps.

The starting point on the site DESY-Bahrenfeld. The injector complex (right) provides the electrons for the facility, the entrance building (centre) gives access to the accelerator. The modulator hall (left) is used for power supply. The liquid helium that cools the accelerator to minus 271 degrees Celsius is produced in the refrigeration hall (not visible).

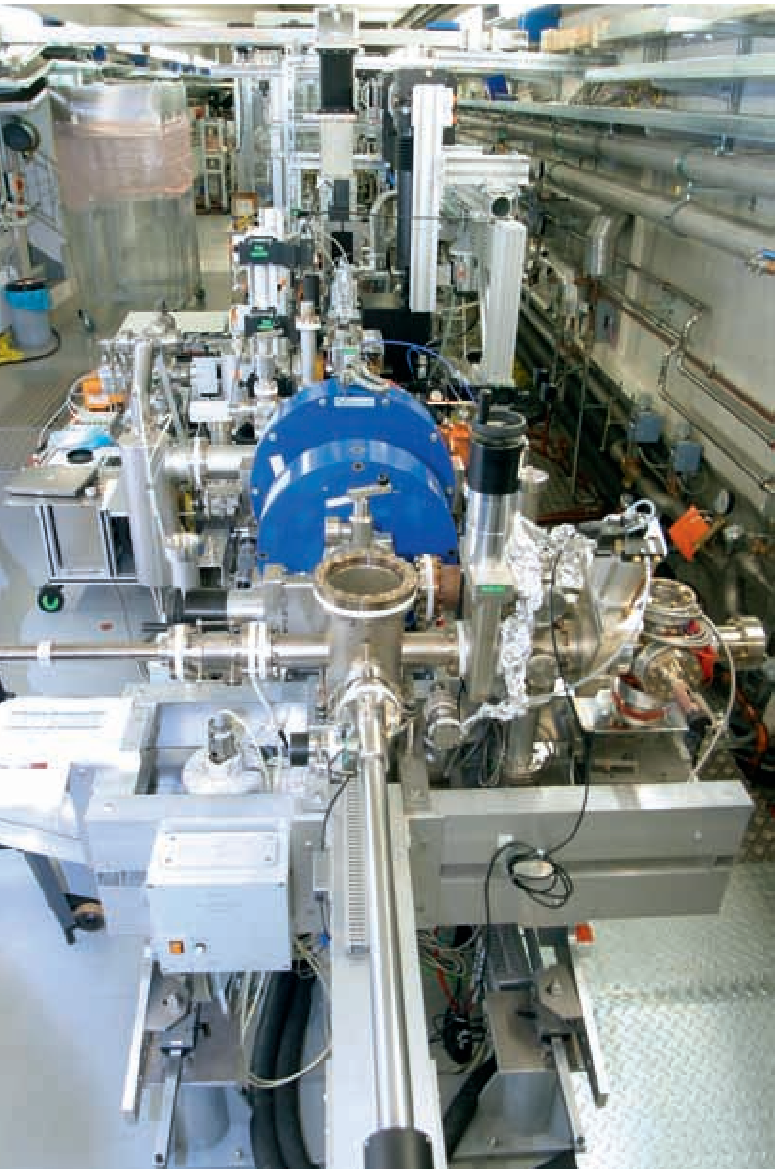
The tunnel of the electron accelerator. The yellow modules hold the cavities in which the particles are accelerated.



PARTICLE SOURCE.

PITZ
Electron sources for X-ray laser and ILC

A growing number of experiments of both a scientific and an industrial nature require extremely intense X-ray radiation of a very high quality. These include filming atomic processes at high temporal resolutions, capturing moving images of the nanoworld, generating holograms of molecules and using X-rays to investigate stellar matter. Generating such radiation requires electron sources with special characteristics. The DESY researchers at the Photo Injector Test Facility PITZ in Zeuthen are developing just such sources.



A test stand for electron sources

As of January 2002, DESY has also been operating a small linear accelerator in Zeuthen. This Photo Injector Test Facility, also known as PITZ, is used for the development and optimization of laser-driven radio-frequency electron sources such as those that will be needed for the European XFEL and the International Linear Collider ILC.

Such facilities require electron beams of the highest quality. In practice, this means that the electron bunches in the beam must be very short and also possess an extremely low emittance. The latter property, which depends on the size and the divergence of the beam, is an important measure of the quality of a particle beam: the lower the emittance, the better the beam can be focused.

At the PITZ test facility, work is under way to develop and test electron sources that produce a particle beam of the requisite high quality. In addition to developing computer simulations and refining theoretical approaches, the scientists at PITZ are also investigating the processes involved in the generation, acceleration and shaping of the electron bunches. Their aim is to optimize beam quality and the operating parameters, such as reliability, of the particle sources.

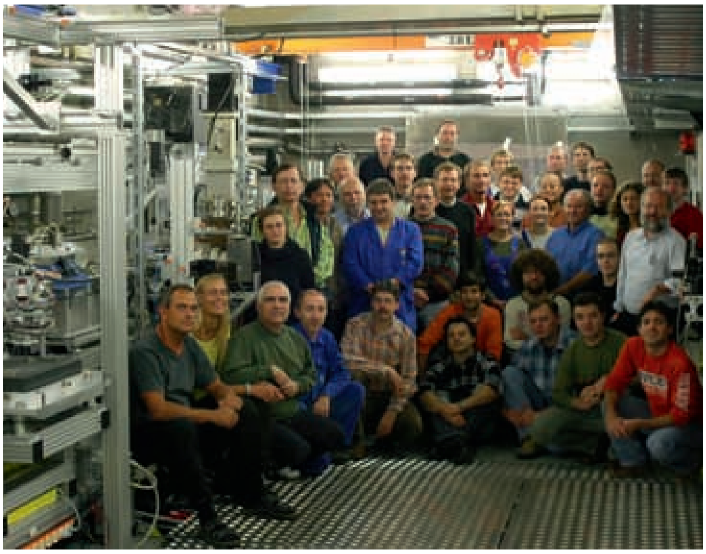
A new laser for slim particle bunches

In order to produce electron beams with the requisite quality for the European XFEL, the scientists at PITZ use a laser to fire high-precision pulses of ultraviolet light at a photocathode located at the head of a cavity resonator. Due to the photoelectric effect, the laser pulses release electrons from the cathode, which are drawn off and accelerated by a radio-frequency electromagnetic field.

The main factor impairing the quality of the resulting electron bunches is the fact that all the particles repel one other because they all have the same charge. The only way to satisfactorily collimate the particles is by accelerating them rapidly and applying an external magnetic field that acts like a lens. The particles then leave the cavity resonator as a dense bunch and fly along the beam pipe, where their properties are precisely measured.

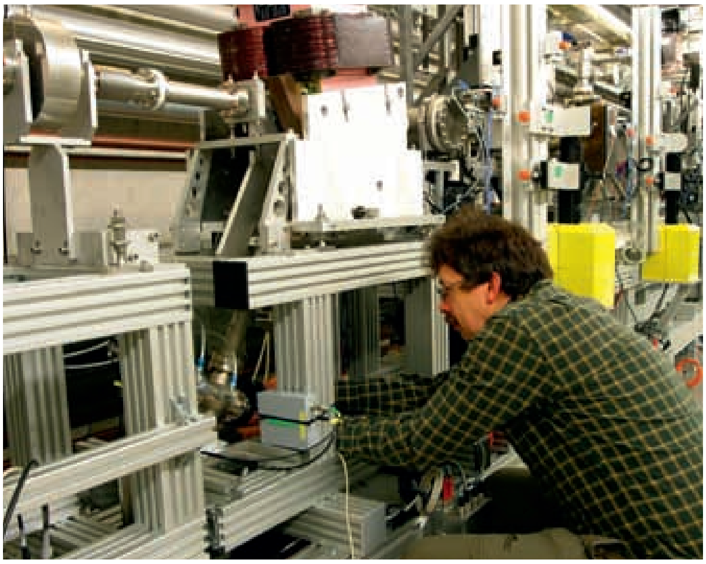
In this way, the scientists can build up an exact picture of the physical processes involved in their generation, which in turn enables them to enhance the quality of the electron source. Measurements made include the temporal length, energy distribution and spatial extension of the electron bunches. In addition, the scientists determine the extent to which the particles' trajectories are parallel to one another. The better these parameters can be optimized, the greater the intensity of the light that will later be generated in the undulators of the European XFEL.

At the end of 2008 a new photocathode laser developed by the Max Born Institute in Berlin was installed at PITZ. It delivers special ultraviolet pulses – so-called flat-top pulses – that are specifically tailored to the beam dynamics of the injector. The facility was also equipped with a new electron source, the copper resonator of which displays much improved vacuum properties thanks to a special dry-ice cleaning process developed in Hamburg. In particular, the photo injector's dark current is considerably less than that of the previous source. As a result, it is possible to produce electron beams with a very low transverse emittance – i.e. beams which have an extremely small diameter and do not diverge – as required for the European XFEL.

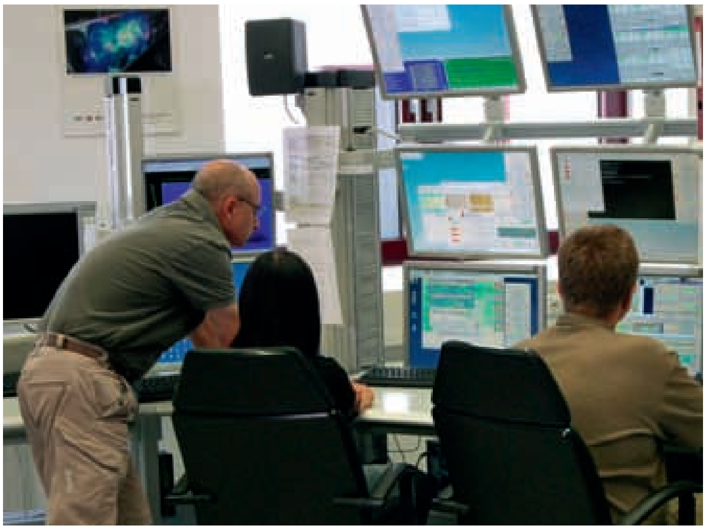


The PITZ team next to the accelerator

Installation of a camera system



The properties of the electron beam are monitored round the clock in the PITZ control room.



PITZ

- Test facility with a linear accelerator at DESY in Zeuthen
- Used to develop and optimize electron sources
- Length: approx. 12 m
- Commissioning: 2002

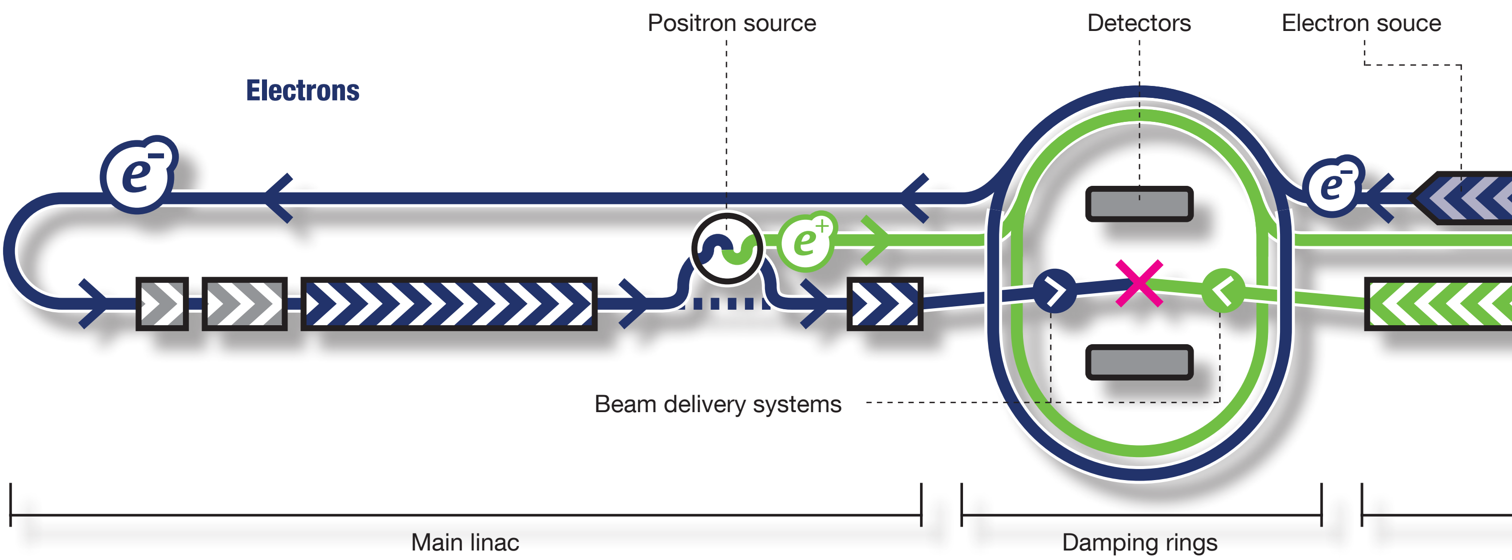
UNCHARTED TERRITORY.

ILC
The project for the future of particle physics

The most powerful accelerator in the world is currently the proton accelerator LHC in Geneva. The LHC will take us on a voyage of discovery that will provide the first-ever insights into the uncharted territory of very high energies. The great riddles of the universe, however, will only be solvable with the help of a further precision machine – a linear accelerator in which electrons and positrons will be brought to collision at highest energies. DESY is playing a major role in the development of one such linear accelerator, the International Linear Collider ILC, which will complement the discoveries of the LHC.

Precision tool at the highest energies

The global particle physics community agrees that the discoveries made using the Large Hadron Collider LHC, which is located at the research centre CERN in Geneva and is currently the world's most powerful accelerator, will need to be complemented by an electron-positron accelerator. Thanks to its uniquely precise measurements, such an accelerator would reveal the secrets of the terascale – the energy realm of trillions of electronvolts (teraelectronvolts) in which the physicists expect to make decisive new discoveries – in exquisite detail. The International Linear Collider ILC, in which DESY is also strongly involved, is one such future-oriented project: an approximately 35-kilometre-long linear accelerator colliding electrons and positrons at energies of between 500 and 1000 billion electronvolts (gigaelectronvolts, GeV).



The ILC consists of two opposing linear accelerators in which electrons and their antiparticles rush toward one another at close to the speed of light. Superconducting resonators boost the particles to ever-higher energies, until they smash together with great force in the middle of the "racetrack". The particle beams collide 14 000 times every second at record electron energies of 500 GeV. Each collision produces numerous new particles, which are recorded by two large detectors. The current baseline design has scope for an upgrade of the ILC to 50 kilometres in length and an energy of 1000 GeV in the second stage of the project.

In contrast to proton accelerators such as the LHC in Geneva, in which composite particles collide with one another, the collisions in the ILC will be between point-like electrons and their antiparticles, positrons, which are also point-like. They annihilate each other to become pure energy, from which new particles are created. Although the energies that can be reached in this way are lower than those attained in collisions involving protons, the results are much easier to interpret than the results from the LHC. This is because the initial conditions of the particle production in the ILC are precisely known and no "fragments" of the colliding particles remain. The ILC is thus a genuine precision machine that ideally complements the LHC proton accelerator, whose real job is to produce new particles in the first place.

Mysterious universe

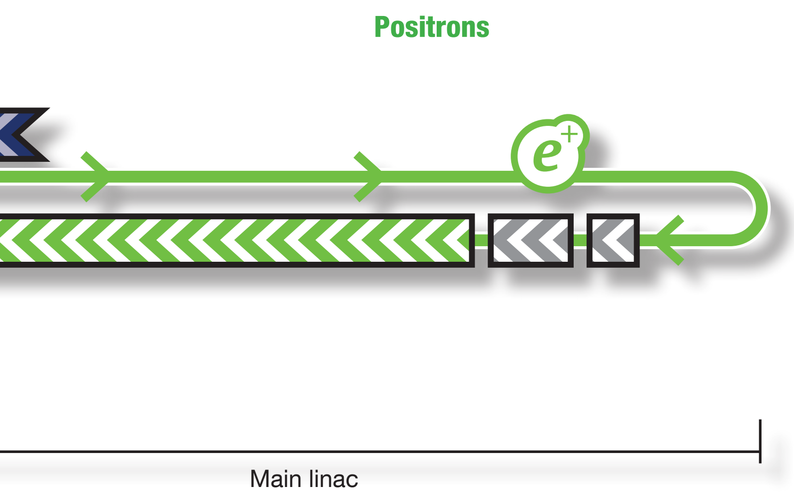
In the recent past, experiments and observations have revealed a surprising gap in our knowledge. It turns out that we can only account for four per cent of the universe. Scientists believe that the remaining 96 per cent consists of mysterious dark matter and dark energy, revealing a universe far stranger and more diverse than they ever suspected.

Thanks to its high energies and unprecedented precision, the ILC will give physicists a new cosmic doorway to the secrets of the cosmos – a doorway beyond the reach of today's facilities. Together the LHC and ILC could unlock some of the deepest mysteries of the universe. With the discoveries of the LHC pointing the way, the ILC could come up with the missing pieces of the puzzle – and provide answers to the century's essential questions about the nature of matter, energy, space and time as well as dark matter, dark energy and the existence of extra dimensions.

DESY in pole position

The ILC is to be constructed and operated as a global project. Worldwide, there were several proposals for such a facility, which differed in their choice of accelerator technology. After a thorough assessment, the committee that represents particle physicists worldwide decided that the future linear accelerator will be realized using the superconducting TESLA technology developed by DESY and its international partners (see page 48). The same superconducting technology is also employed in the free-electron laser FLASH at DESY and the European XFEL X-ray laser, which is currently under construction in the Hamburg region – an outstanding example of the successful synergies provided by the multiple use of a completely new technology. In other words, DESY remains excellently qualified to continue playing a leading role in the development of superconducting accelerator technology.

At the same time, the DESY researchers are also involved in the development of further important components for the ILC accelerator – mainly as part of international projects such as the TESLA Technology Collaboration or EU projects such as EUROTeV and ILC-HiGrade, which are being coordinated by DESY. The work involved includes the development of damping rings and polarized positron sources; studies on beam diagnostics, beam dynamics, beam stabilization and luminosity optimization; measurement of ground motion; and establishing a global accelerator network to enable remote monitoring and control of the accelerator. The DESY researchers are also making a major contribution to the design and development of the high-precision detectors that will record the particle collisions in the ILC.



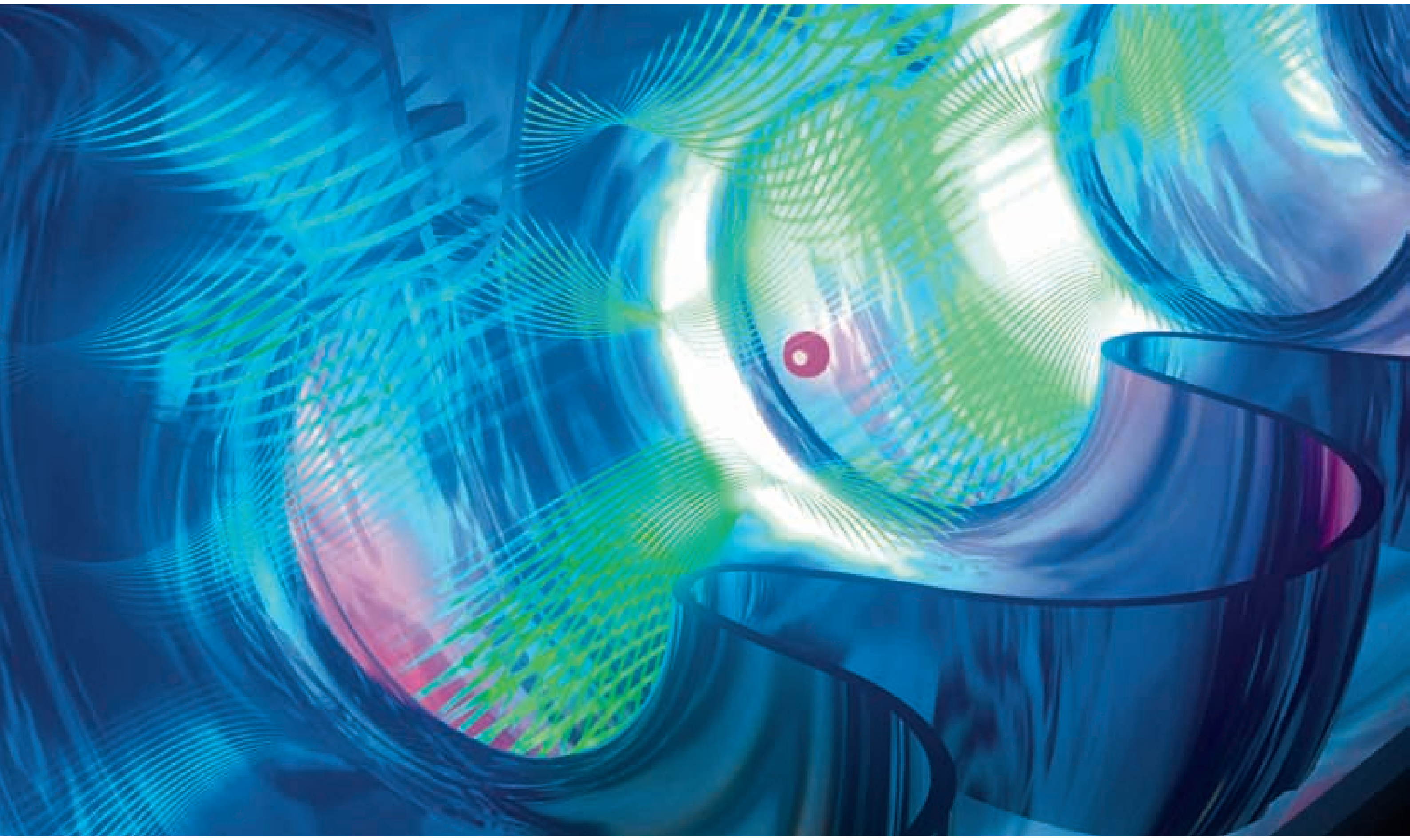
ILC

- Electron-positron linear accelerator
- Length: ca. 35 km
- Being planned, location still to be decided
- Two experiments at one collision zone
- Participation: 2000 scientists from more than 25 countries

COLD FRONT.

TESLA technology
Powering the accelerators of the future

It was back in the early 1990s that DESY, together with partners from abroad, first started work on the development of a pioneering superconducting accelerator technology. The concept has proved so successful that it was chosen for the next major project in the world of particle physics, the International Linear Collider ILC. At the same time, it has also turned out to be ideal for operating a free-electron laser in the X-ray region. As one of the leading institutions in this field, DESY is playing a major role in the further development of the superconducting TESLA technology.



The TESLA project

It is now almost 20 years ago that work first began on developing the next major facility for particle physics: a linear accelerator capable of boosting electrons and their antiparticles, positrons, to energies ranging from 500 to 1000 billion electronvolts (gigaelectronvolts, GeV). Under the leadership of DESY, the international TESLA Collaboration put together a design concept based on the use of superconducting cavities made of the metal niobium. While this technology offers decisive advantages with regard to acceleration capability, it also represents a massive stride into unexplored technological territory.

It is the use of superconducting accelerator technology that marked the decisive difference between the TESLA and rival projects, which were to rely on conventional, normally conducting technology. In the course of the development work for TESLA, it emerged that this type of superconducting linear accelerator would also be ideal for operating a free-electron laser in the X-ray range. TESLA was therefore planned as a combined facility, comprising a linear collider for particle physics experiments and an integrated X-ray laser for photon science.

Pioneering work for TESLA

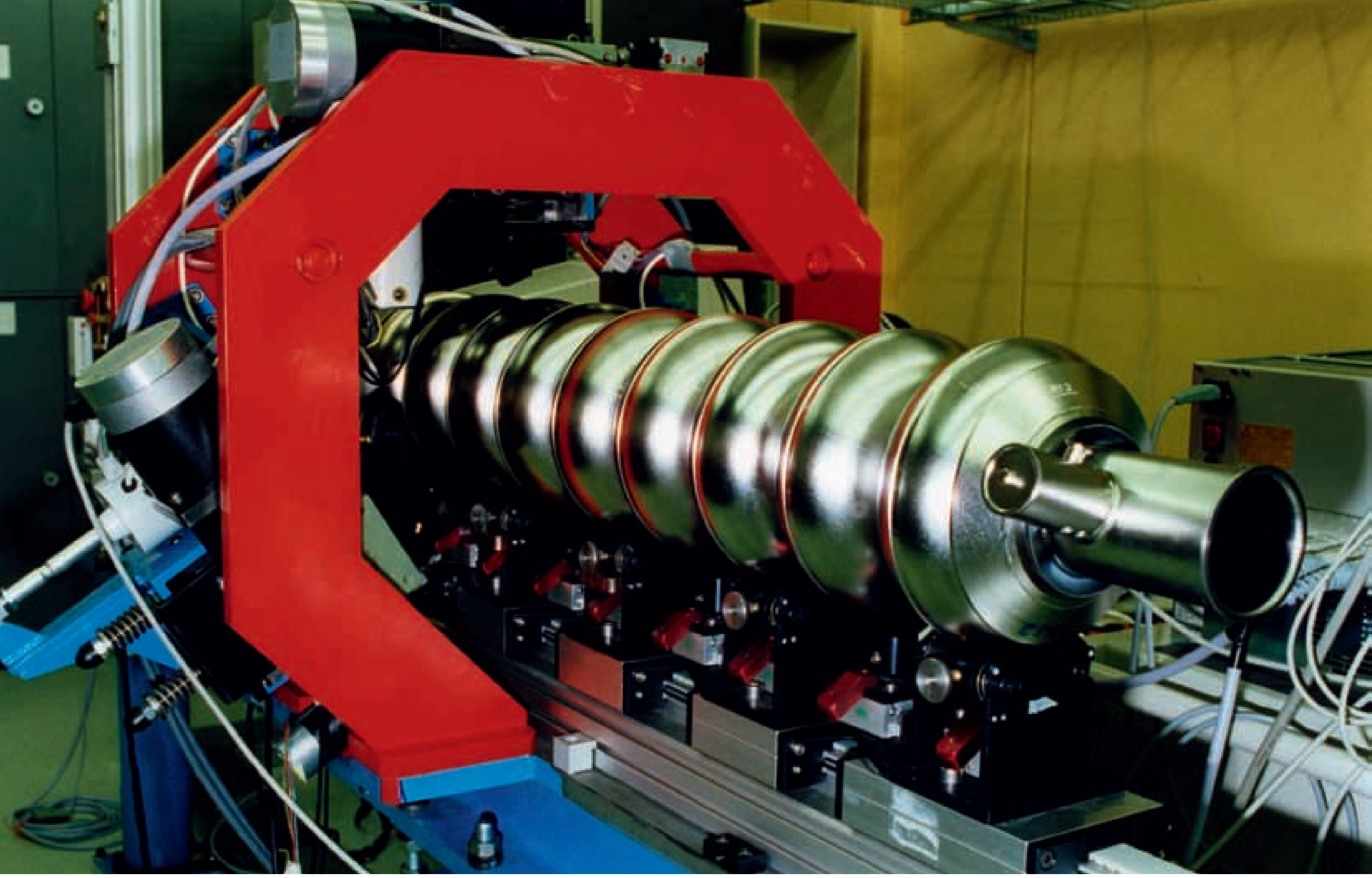
In order to test the technology for TESLA under realistic conditions, the TESLA Collaboration constructed a fully functional test accelerator at DESY – the 100-metre-long TESLA Test Facility TTF – which featured all of the components required for the operation of a superconducting linear accelerator. Thanks to the quality of the development groundwork, the TTF got off to a flying start in 1997. Indeed, the first eight of the superconducting niobium cavities immediately achieved an accelerating field strength (gradient) in excess of the 15 megavolts per metre (MV/m) originally planned. This was a world premiere and also marked a decisive advance on the early days of the project, when the maximum gradient achievable in beam operation was only 5 to 8 MV/m. Meanwhile, it has proven possible to more than double the initially recorded value of 15 MV/m. In this way, the TESLA Collaboration has been able to deliver conclusive proof of the technical feasibility of a superconducting electron-positron linear accelerator.

The TTF team then went on to demonstrate the feasibility of the second part of the TESLA project, the superconducting X-ray laser. The decisive proof arrived at the start of 2000, when the TTF – following its conversion to a free-electron laser – first produced laser pulses with a wavelength of less than 100 nanometres. After it had successfully fulfilled this mission, the TTF was extended and converted to FLASH, the world's first ever free-electron laser in the soft X-ray range. Since 2005 it has been available to scientists from around the world for their experiments (see page 36).

From TESLA to European XFEL and ILC

At the beginning of 2003 Germany's Federal Ministry of Education and Research took a significant decision in favour of the X-ray laser part of the TESLA project. Whereas the X-ray laser was granted approval in principle as an independent European facility, a resolution regarding the linear collider was deferred pending global developments in the rest of the field. De facto, the two projects were thereby separated. Today the X-ray laser project is known as the European XFEL and is being realized in Hamburg and Schleswig-Holstein with substantial participation by DESY (see page 40). The responsibility for the linear collider project has been transferred to the international level.

Following assessment of the various accelerator projects submitted, including TESLA, the international commission responsible decided in summer 2004 that the future linear collider – henceforth to be officially known as the International Linear Collider ILC – would be based on the TESLA technology developed by DESY and its partners. Since then, the development and planning work for the ILC has been proceeding at full speed, with a global collaboration now comprising more than 2000 scientists from over 25 countries currently working on the project. As experts in superconducting accelerator technology, DESY and its partners from abroad – now known as the TESLA Technology Collaboration – are playing a major role in these developments.



Test of a superconducting niobium cavity

Top-quality research at DESY

Three different facilities are based on the superconducting TESLA accelerator technology: the roughly 300-metre-long free-electron laser FLASH, the 3.4-kilometre X-ray laser European XFEL and the approximately 35-kilometre linear accelerator ILC. The operation of FLASH, as well as the construction and subsequent operation of the European XFEL, therefore provide DESY with crucial insights regarding the ILC – for example, in terms of the challenges involved in developing, in partnership with industry, highly sophisticated accelerator components to technological maturity, and being able to mass produce such parts in line with required quality standards.

ILC development will also benefit from the experience DESY will gain during the tunnel construction for the European XFEL and the installation of equipment inside it. A total of more than 200 people at DESY are currently working on FLASH, the European XFEL and preparations for the ILC. Many of them are involved in all three projects, which generates important synergy effects that set DESY apart from other research centres participating in the ILC project.

The advantages of superconductivity

TESLA technology is based on special accelerator structures known as cavity resonators that are made out of the metal niobium. When this metal is cooled to below minus 264 degrees Celsius – the kind of temperature that is otherwise found only in outer space – it loses all of its electrical resistance and conducts current without any energy loss, i.e. it becomes a superconductor. This property offers major advantages for particle acceleration, as power losses in the superconducting resonator walls are extremely low and almost all the power can be transferred to the particle beam. This results in a vast reduction of energy consumption. In addition, the particle beam thus created is of extremely high quality because due to their vanishingly small electrical resistance, the resonators with can be made bigger than those designed for normal conductivity, resulting in fewer interference fields. Electrons can then be packed into fine, highly precise bunches, while at the same time many electron packets can be accelerated in rapid succession.

The result is a particle beam with a very small beam cross-section and high beam power. This in turn means that a particularly high collision rate of the accelerated electrons and positrons can be achieved, which is the ideal prerequisite for new discoveries in particle physics. A particle beam with a very high bunch repetition rate also provides an ideal basis for the operation of a free-electron laser in the X-ray region.

TESLA technology is extremely challenging, however. In order to make the entire acceleration section superconducting, the complete length of the facility must be cooled down with liquid helium to minus 271 degrees Celsius. To this end, the niobium resonators are placed in so-called cryostats – metre-thick, extremely well-insulated metal tubes which, along with eight resonators, also contain the transport lines for the liquid helium, as well as various control systems. Manufacturing the superconducting cavities is also a delicate process. Even the slightest surface unevenness, or just a couple of dust grains on the resonator surface, would be enough to cause superconductivity to break down and make the resonators unusable. That's why the accelerator modules are manufactured and assembled in a cleanroom that contains one hundred thousand times less dust than is found in normal city air.

Maximum gradient

A major objective of the further development of TESLA technology for use with the ILC accelerator in the future is to increase the acceleration gradient of the superconducting niobium cavities. Plans call for electrons and positrons to be accelerated reliably along the entire length of the ILC at 31.5 megavolts per metre (MV/m) so as to ensure that they attain the required final energy. The theoretical limit of superconducting technology is around 50 MV/m, and some one-cell resonators with a gradient of as much as 43 MV/m have already been built. Nine-cell cavities such as those planned for the ILC have achieved gradients of up to 40 MV/m in individual tests and approximately 30 MV/m in groups of eight within accelerator modules. Just how the gradient can be increased to the required ILC level in a reliably reproducible way is being intensively studied also at DESY. The processes for manufacturing and treating the surface of the niobium cavities both play a vital role here.

The inside of the resonators must be extremely smooth and clean, for example. An unevenness measuring just a few micrometres can cause a local peak in the electromagnetic field, thereby generating a cloud of electrons within the interior of the cavity. This cloud raises the temperature where it meets the cavity surface, causing the superconductivity to break down. Together with international partners, DESY scientists have therefore developed an electropolishing technique that uses an acid mixture subjected to a flow of current to polish the niobium surfaces to a mirror-like finish. The results to date have been promising, as the electropolished surfaces are much smoother and thus cleaner than those cleaned using conventional chemical polishing techniques. Superconductivity can thus be maintained up to significantly higher gradients. This electropolishing technique has meanwhile been transferred to industry and will be used for the manufacturing of the cavities for the European XFEL.

New production techniques

Another idea to improve the quality and thus raise the gradient of the cavities is to produce them from large niobium crystals, or even monocrystalline niobium. The crystal lattice in conventional polycrystalline niobium is not uniform, which causes breaks and differing orientations in the lattice. Such grain boundaries can inhibit resonator performance. Larger crystals with fewer grain boundaries, or single crystals in which all of the niobium atoms are in a homogeneous, uniformly oriented layer of the crystal lattice, result in much smoother and cleaner surfaces. This technology could guarantee better reproducibility and lower the fluctuation range of the gradients of various cavities.

The initial prototypes manufactured from large-grain niobium crystals or monocrystalline niobium have already produced outstanding results. For example, working in cooperation with the company ACCEL, DESY researchers were able to build a single-cell cavity from one niobium monocrystal that achieved an acceleration gradient of around 40 MV/m. Particularly challenging here is the welding of the cavity half cells, since the niobium atoms in these cells must have exactly the same orientation in order to ensure that no grain boundaries form on the welding seams. This maintains the monocrystalline structure, which means the complete cavity cell basically consists of a single crystal. The associated manufacturing technique developed by DESY/ACCEL has since been patented.

Because the production of monocrystalline niobium remains very expensive, it is not yet possible to utilize single-crystal technology for series production of the ILC resonators. Researchers are therefore currently concentrating on the production and optimization of cavities made from large-grain niobium crystals, which can be manufactured more simply and cheaply. Several nine-cell resonators produced in this manner already exist, and the best of them has achieved a promising gradient of 38 MV/m.

Accelerator modules on the test bench

Simply optimizing the niobium cavities is of course not enough to meet ILC specifications. As is the case with FLASH and the European XFEL, the ILC will probably be fitted with accelerator modules containing eight cavities each. These modules will not only allow the cavities to be cooled down to minus 271 degrees Celsius, but also hold numerous important components such as input couplers for the radio-frequency electromagnetic field that accelerates the particles, antennas for damping interfering electromagnetic oscillations, magnets for focusing the beam, diagnostic instruments for measuring beam position and beam current, and a multitude of wires and cables etc. All of these elements must operate at high performance, be perfectly attuned to one another, and in some spots fit together precisely down to a tenth of a millimetre.

To ensure that DESY would also be able to test and optimize the accelerator modules for FLASH, the European XFEL and the ILC independently of FLASH operation, a new test stand went into service at DESY in 2007. This test rig was financed with funds from the European XFEL research and development programme and with EU funding from the EUROFEL project. The test stand makes it possible for the first time to study the complete 12-metre-long superconducting modules and prepare them for operation before they are installed in the FLASH linear accelerator. That not only frees up valuable user time with FLASH, which would otherwise have to be expended for module testing; it also enables quick prototype tests to be carried out for the European XFEL and the ILC. This approach also makes it possible for experts to gather experience with the modules' operation, experience that can later flow into work with the European XFEL and the ILC.

Cold shocks...

The test stand has been running full time since going into operation. The first module tested was subjected to a large number of hot-cold cycles, among other things. In this test procedure, the module was cooled to minus 271 degrees Celsius and then warmed back to room temperature in order to examine the behaviour of all of its internal components under such extreme conditions. Here it was found that the input couplers are thermal bridges that allow ambient heat to more easily enter the module. As the tests revealed, however, the additional thermal load of the couplers is lower than the maximum permitted. Another positive finding was that the large number of vacuum connections remained leak-proof even under the substantial stress of these thermal cycles.

Even a minimal movement of the module components as a result of temperature changes can impair the quality of the accelerated particle beams; as little as a fraction of a millimetre can be enough. That's why sensors were placed within and on the surface of the modules in order to determine whether vibrations occur inside and the extent to which the components shift relative to one another – at room temperature, at minus 271 degrees Celsius, with or without radio-frequency, and even when trucks drive past.

The measurements show that thanks to the way the modules are suspended, external stimuli do not cause vibrations of the accelerator structures themselves. The vibration study group thus concluded that the design of the modules in this regard is outstanding. The analyses conducted are also very important in terms of the decision as to where to locate the ILC. Combining their results with seismic ground motion data from various sites makes it possible to precisely predict the movements of the accelerator at each location, a very important factor in the selection of a suitable site for the ILC.

Preparing for final texts of the superconducting resonators

Each accelerator module contains eight superconducting cavities cooled to minus 271 degrees Celsius.



Crash tests...

The worst thing that could happen to an accelerator module under vacuum cooled down to an extremely low temperature would be a failure of the various vacuum systems. For this reason, yet another important study was carried out at DESY in 2008 in the form of a series of crash tests that simulated a variety of worst-case scenarios under controlled conditions. Among other things, small and large vacuum leaks in insulating layers and in module beam pipes were simulated by flooding these with air, sometimes quickly, sometimes slowly. The aim here was to ensure that the modules meet European regulations regarding pressure vessels and that, should the worst happen, any problems will remain confined to the inside of the module. The scientists were also looking to determine whether the planned safety measures were sufficiently efficient (e.g. whether the safety valves had been placed in the right locations). In addition, they wanted to identify which components could be expected to suffer damage in such an emergency and would therefore have to be replaced.

The crash test started with a loud bang and big clouds that formed at the safety valves. When air at room temperature flows into an accelerator module whose temperature is around 300 degrees Celsius lower, the air immediately freezes out by condensing on the cold surfaces. The condensation energy is transferred to the liquid helium used to cool the resonators to minus 271 degrees Celsius. The helium vaporizes abruptly and escapes through the safety valves. In such a test, the air flows into the module at nearly the speed of sound, which explains the loud bang.

Fortunately, crash-testing the insulating vacuum caused only minor damage to the outer shells of the multilayer insulation and the outer thermal shield. It was possible to immediately cool down the module again, and the testers noticed no decrease in the cavities' operating performance. Of particular interest to the scientists, however, was the flooding of the beam pipe and the cavities themselves. They found that it actually takes the warm air five seconds to travel from one end of the module to the other. This means that in the event of air infiltration, there will still be a few seconds left to shut the beam pipe valves and thus protect as many resonators as possible. The impact of the air flooding on the cooling system was also much smaller than what had been feared. As expected, after the resonators were powered up again, their gradients had declined substantially due to the flooding of the beam vacuum. However, the test also showed that air infiltration on such a scale would not completely shut down accelerator operations as long as only a few cavities were affected. Should this type of infiltration occur, the air could simply be pumped out, after which the facility could be started up again.

... and assembly manuals

In order to prepare for series production of the accelerator modules for the European XFEL and, at a later date, the ILC, DESY is now taking measures to ensure that the vast store of module construction expertise it has accumulated over recent decades is shared with project partners. Indeed, the European XFEL will require around 100 such modules and the ILC nearly 2000 – in other words, teams around the world must soon be ready to assemble thousands of accelerator modules. That explains why numerous guests from Japan, Korea and the USA, as well as industry representatives, have already visited DESY to watch the assembly team put the modules together. Industrial companies are especially interested in how the assembly process can be converted to series production on a larger scale, and which process steps might need to be changed or improved to do this.

A detailed assembly manual was produced for the modules. The instructions are highly complex, as 1200 individual components must be joined at the highest level of precision and under extremely restrictive cleanroom conditions. From the production of the superconducting resonators to their assembly in cleanrooms, the installation of couplers, antennas and test devices must also be documented in complete detail because each of the many extensive assembly steps consists of hundreds of individual work packages.

The first to benefit from the manual were the physicists, technicians and engineers at Fermilab in the USA, who were assisted by DESY experts in 2007 as they learned how to assemble into a module the 1200 individual components delivered by DESY. This was in fact the first accelerator module ever assembled outside of DESY. Fermilab staff weren't the only ones to benefit from this cooperation – the DESY team also gained valuable experience in how to ensure that their specialized knowledge is passed on as efficiently as possible.

The first two cryostat prototypes for the European XFEL (the "shells" of the modules, including most of the refrigeration technology) have already been manufactured in industry, and China's IHEP research centre supplied a further cryostat. The complete modules are then assembled at DESY; the CEA research centre in Saclay, France, will be responsible for this task at a later date. The launch of series production activities for the European XFEL is thus under way. The experience that DESY, other research institutes worldwide and industry will gain from this launch will also greatly benefit the ILC project.

Installation of an accelerator module in the free-electron laser FLASH

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Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

Hamburg Location: Notkestraße 85, D-22607 Hamburg
Tel.: +49 40 8998-0, Fax: +49 40 8998-3282
desyinfo@desy.de, www.desy.de

Zeuthen Location: Platanenallee 6, D-15738 Zeuthen
Tel.: +49 33762 7-70, Fax: +49 33762 7-7413
desyinfo.zeuthen@desy.de

Author
Ilka Flegel, Textlabor, Jena

Realization and editing
Ute Wilhelmsen
Ilka Flegel, Textlabor, Jena

Design
Jung von Matt/brand identity GmbH, Hamburg

Layout
Heike Becker

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Photographs and graphics
DESY
European XFEL
Lars Berg, Münster
Frank Bierstedt, Meine
form one visual communication
Peter Ginter, Lohmar
Marc Hermann, Tricklabor
Kontor B3, Hamburg
Rüdiger Nehmzow, Düsseldorf
David Parker, Science Photo Library, London
Dominik Reipka, Hamburg
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Christian Schmid, Hamburg
Manfred Schulze-Alex, Hamburg
Thomas Schwörer, Hamburg
Option Z, Thomas Plettau, Frankfurt

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